ENERGY BASIS FOR MIAMI, FLORIDA,
AND OTHER URBAN SYSTEMS

By

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This dissertation presents a systems study of Miami,

Florida, with data collected for the years 1950-72, cross-

correlation analysis of the data, calculation of urban in-

dices, computer simulation of mathematical models, construc-

tion of a land use map, calculation of major economic, fossil

fuel and natural energy flows, estimations of energy avail-

able from solar energy technology, and a theory relating eco-

nomic competitiveness to the ratio of natural to fossil fuel

energies. The urban system of Miami and Dade County, Florida,

was used as a study area but the theory and approach could be

used for any urban system.

An overall detailed model of the urban region of Miami,

Florida, was created showing major flows and storages in the

system and time series data were collected for 1950-72.

Cross-correlation analysis showed significant levels of cor-

relation between the rate of change of fossil fuel use and

the rates of change of population, budget, sales tax, income,

building structure, and number of telephones. Calculation

of several urban indicators for 1972 showed a fossil fuel

energy density of 300 Kcal/m^2/day in the urbanized area, a

per capita energy consumption of 53.8 x 10^6 Kcal/capita/yr,

a ratio of natural to fossil fuel energies of 0.25, a devel-

oped area of 260 square miles, a building growth of 150

million square feet, and a rate of development of 6.5 square

miles per year. Tables and graphs of these and other vari-

ables are presented from 1950 to 1972 to identify trends.

Based on the overall model of Miami, several mathemati-

cal models for the Miami-Dade region were simulated using

analog computers. These models consisted of systems of first

order in time, non-linear differential equations which in-

cluded fossil fuel energy flows, main economic flows, exter-

nal price functions, building structure, natural energies, and

population. These equations were derived from a general

theory of human systems based on energetic and ecological

principles. These models were simulated for several linearly

increasing functions for price and several sets of available

energy functions. Based on existing available energy trends

and the rate of increase of price, the urban region of Miami

and Dade County should reach a maximum point of growth around

1976. If additional net energy above past levels can be

supplied in the future, then growth may continue until 1985

with the population leveling at about 1.6 million. Increas-

ing prices for fuels cause structure to peak earlier and

sooner while diminishing the use of fossil fuels.

Tables of economic and energy flows were constructed through calculation or estimation. To calculate the energies associated with the natural systems in the county a land use map was drawn and subsystem areas determined. Estimating the productivities of these systems on a per area basis then allowed calculation of total energy flows. The energies associated with winds, tides, waves, and fresh/salt water concentration gradient were also calculated. These energies were compared to fossil fuel energies by using the concept of energy quality and it was found that the ratio of natural to fossil fuel energies changed from 0.77 in 1950 to 0.25 in 1972. It was hypothesized that regions with higher natural to fossil fuel energy ratios can compete more effectively since they have greater natural energy subsidies.

It was calculated that recycling of garbage could produce, at most, 2.7% of the fossil fuel energy consumption while solar energy technology used for hot water heating could save, at most, 3.5% of the total fossil fuel energy used in 1972. The energy flows associated with primitive, electrical, natural, gas, and solar water heaters are presented. The relationship of prices, money, and energy flows are discussed for urban regions in general and related to the future of Dade County in particular.

As a final point of interest, an order-disorder formulation of the urbanization of South Vietnam was constructed which included main flows of money, growth of natural and urban systems, and destruction due to herbicides and general

warfare.   Results are presented for an herbicidal pulse last-
ing five years and different levels of U.S. aid.

INTRODUCTION

Perhaps the most complex and least understood systems of man are cities and urban regions which seem necessary for exchanges of energy, information, money, and goods between men and institutions. Understanding of urban systems is desperately needed for coping with the last thirty years of the twentieth century because of the intense and rapid changes occurring. The United Nations estimated that the urban populations of the underdeveloped countries will quadruple by the year 2000 and that those of the developed nations will double. Will this trend continue or will it change as a function of available world supplies of energy? Can energy predictions be used to implement accurate and adequate planning for the basic needs of these urban populations? Can economic forces driving migrations be ultimately reduced to energetic considerations and these be used to predict migrations, availability of jobs in cities, and mechanization of agriculture on the farms?

The energy crisis of 1973 dramatically outlined the dependence of the American economy and its subsystems on fossil fuel energies. In order to relate the structure and functions of cities and their supporting regions to energy, models and calculations were made to show main principles for

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urban growth and change considered in overview. In this
study a general energy basis for cities is presented.
Detailed applications, evaluations, and simulations were
applied to Miami-Dade County, Florida and other cities.

The contributions of natural system energies are impor-
tant in Dade County because of their multiplier effects on
tourist flow and the general life support of the basic func-
tions of maintaining air and water quality. Is there a
limit to fossil fuel development in relation to natural ener-
gies above which the system loses tourist or economic viabil-
ity? What is the value of these energies to a future steady-
state urban system for possible energy futures? The future
will be characterized either by a low level of fossil fuel
availability and no net nuclear energy source or further
growth based on new energy sources. By taking a macro-scale
approach to the urban system this dissertation presents a
theoretical framework for understanding cities.

Urban growth in the United States has accelerated in
recent decades. This has facilitated competition with the
rest of the world by maximizing growth rates and the utili-
zation of unused energy reserves. Urbanization has followed
the maximum power principle which says that those systems
survive and compete best which maximize their power flow
(Lotka, 1922). High energy components of cities have emerged
and have required enormous resources for support so that the
city system can continue to function. Is this trend shift-
ing? Since there is little experience with a steady-state

economy, serious study and thought are needed to determine the
characteristics and behavior of a steady-state city. There
is a plethora of studies on individual projects and aspects
of cities including population, transportation, economics,
racial distributions, housing, water supply, etc., but very
few studies for an urban region as a whole with consideration
of some basic parameters and with energy as a common denomi-
nator for appraisal of the basic outside forcing functions.
Many have felt that a model of an entire urban region is too
complicated, with thousands of parts recognized when one
examines a city in micro-scale. However, if a complex system
is considered at a macro-scale level by lumping components, a
manageable model can be constructed to show gross effects
which eventually are propagated down to the micro-scale level
(Odum and Peterson, 1972).

A very simple model showing some of the basic inflows to
a city along with some of the principal storages within the
system is diagramed in Fig. 1 (for an explanation of the
symbols, see Fig. 3 in the Methods section). The source
labeled income represents the flow of money entering the
system and is shown to be pumped by natural energies. This
represents, for example, tourism. The source labeled re-
sources includes all the purchased energy and materials neces-
sary such as fossil fuels, food, water, goods and people and
the source labeled free natural energies represents the work
services of the natural system in support of man. The inter-
nal storages consist of structure, money available to spend,

Fig. 1. Simplified model of an urban system showing flows of money, natural energies, and fossil fuel resources into the system. Price is determined external to the system. Storages within the system are money available to spend, building structure, and number of people, all of which interact multiplicatively with external sources to generate growth.
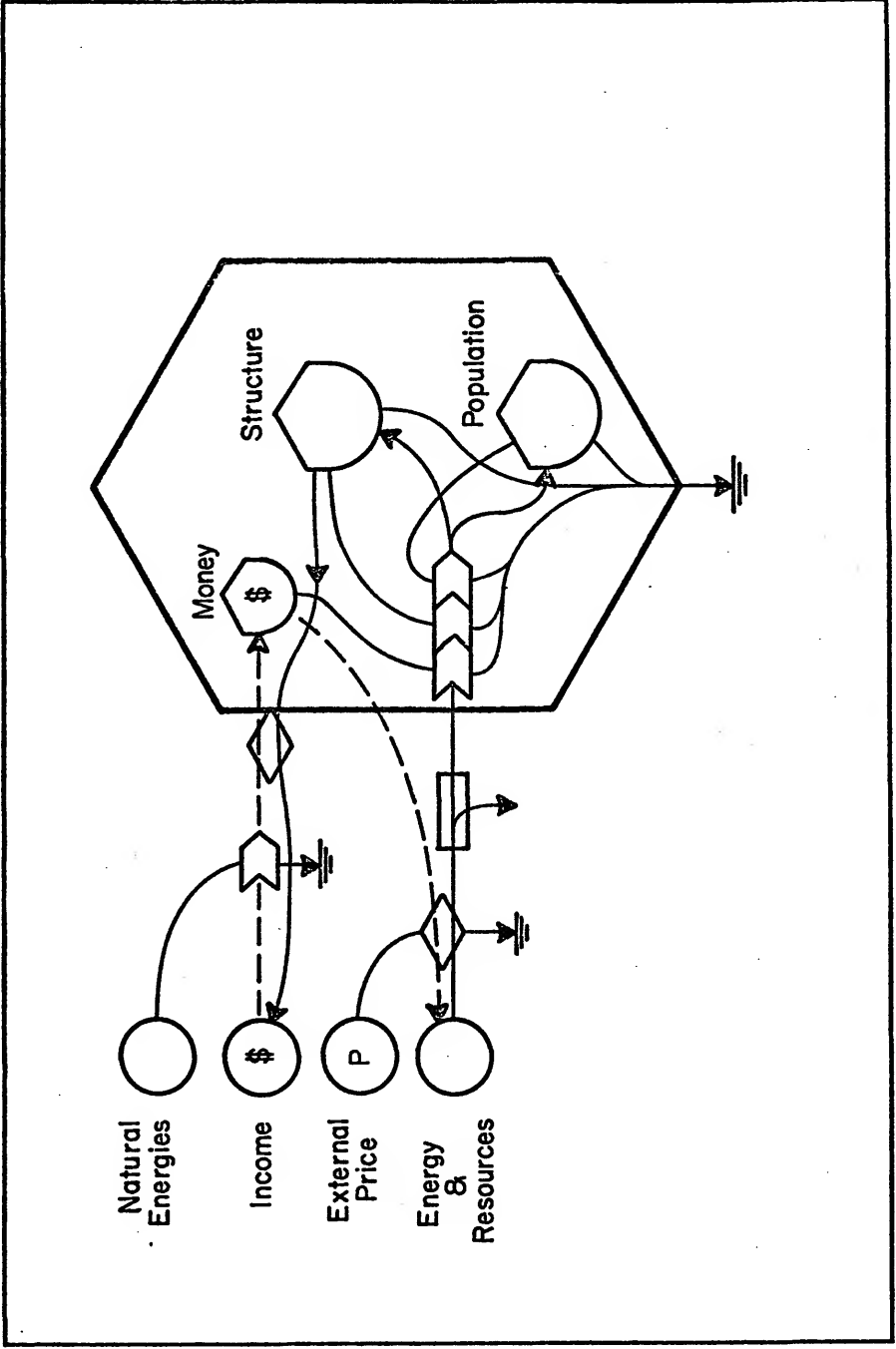
and number of people. The structure, population and money storages of the system act in multiplicative action to add new structure and population to the system. Money flow from outside can come from many sources. The heat sink drains from storages represent depreciation while those at the multiplier symbols represent heat losses due to energy conversions. Can a model as simple as this with its aggregation show, through simulation, the change in the growth of structure as a function of changes in the supply of money and resources along with changes in prices occurring in the larger economy encompassing the city? Simulation results of models similar to this are presented. Theoretical studies are included to suggest a class of overview mini-models which can be generally substituted for detailed city models with similar results.

American urban systems have been characterized by rapid, successional type growth without much recycle. The model in Fig. 1 does not show any explicit recycle pathways but if this were a steady-state or declining city recycle pathways would be included. In natural ecosystems there is a cycle of growth and decay in which the dead parts are reorganized into living structure through an interaction with an outside energy source, usually sunlight. This can be thought of as a general order-disorder cycle which is representative of all processes in nature. This principle is applied later in this dissertation to the urbanization of an entire country, namely, South Vietnam.

Dissertation Research Outline

The purpose of this dissertation is the study of the
energy-economic basis for urban systems with specific refer-
ence to the region of Miami-Dade County, Florida. To this
end models were developed which indicated the response of
the urban system to available energy and outside price func-
tions over time. Time-series data were collected for the
urban system of Miami-Dade County for as many of the gross
parameters of the urban system as it was possible to collect
data for. These parameters included energy consumption,
building structure, population, money flows, land development,
water consumption, tourist flows, transportation structure
(vehicles), waste generation, etc.

The creation of conceptual and mathematical models were
accomplished using the energese symbols (H. T. Odum, 1971) for
detailing the overall system functions and interactions.
These models are usually too complicated for simulation but
indicate major pathways, interactions and, along with descrip-
tive tables indicating numerical values, allow comparisons
between the magnitudes of different pathways. Starting with
the overall complex model of the urban system, several simpli-
fied models were derived and simulated in order to determine
the response over time to different energy functions, price
functions and money income. Although the exact numerical
value of certain parameters is uncertain, e.g., available
energy, simulations are conducted for parameter variation so

that families of curves are generated. This at least gives
an estimate of a predicted value range for variables of
interest within the system. All of these models involve the
solution of systems of first order, non-linear equations,
which means they contain first derivatives with respect to
time and products of two or more state variables, equations
of the form

$$\frac{\partial Q_i}{\partial t} = \sum_{K=j}^{P} I_{iK} + f_i(Q_1, \ldots Q_N; I_1, \ldots I_j)$$
$$i = 1, 2, \ldots, N$$

where I_j and I_{iK} are some general forcing functions, Q_i are
the state variables, f_i is a non-linear function, and N is
the number of equations. The combined system of equations
represents a system of Nth order. Thus, the simulations con-
tained herein investigate the behavior of non-linear system
theory applied to urban systems along with the applicability,
sensitivity and validity of such formulations. This is of
importance because of the overwhelming use of linear, economic
models. Aside from simulation results correlation analysis
was conducted and interpretation of the time-series data was
attempted. The accumulation of the data for the Miami region
is important in itself for they can serve as a reference for
other studies.

Land areas of subsystems contained within Dade County
were calculated from land-use maps derived from aerial photo-
graphs. These subsystems included urban and natural systems
such as residential and commercial areas, swamps, hardwood

hammocks, and mangrove swamps. Estimates were made of the productivity of each of these systems and an energy system spectrum was calculated. The general theory of urban systems is discussed and calculations of basic energy indicators were made for the Miami-Dade system which can serve as yardsticks for comparisons with other urban systems. Energy budget calculations were also made to estimate the energetic value of money flows in the system and contributions from solar energy technology were estimated.

Description of the Study Area

Located in the southern portion of the state of Florida, latitude 25°47' North and longitude 80° West, the Miami-Dade County region is an area of approximately 2,000 square miles (see Fig. 2). Originally covered by vegetation of the type found in the Everglades National Park, it has rapidly been transformed since extensive drainage, dredge and fill operations, and agricultural and urban development began in the early 1900's. Most of the urban development has occurred along an above-sea level strip of land paralleling the east coast known as the coastal ridge. In the process of growth, many species of plants and animals have been destroyed and as much as 90% of the wildlife of the Everglades has disappeared. However, the magic of the name Miami as a subtropical paradise was maintained for a long time and tourists were attracted by the sunny beaches, mild weather, natural

Fig. 2. Map of Florida showing the location of the
        urban region of Dade County.

ATLANTIC
OCEAN

GULF OF
MEXICO

FLORIDA

STUDY AREA:
DADE COUNTY
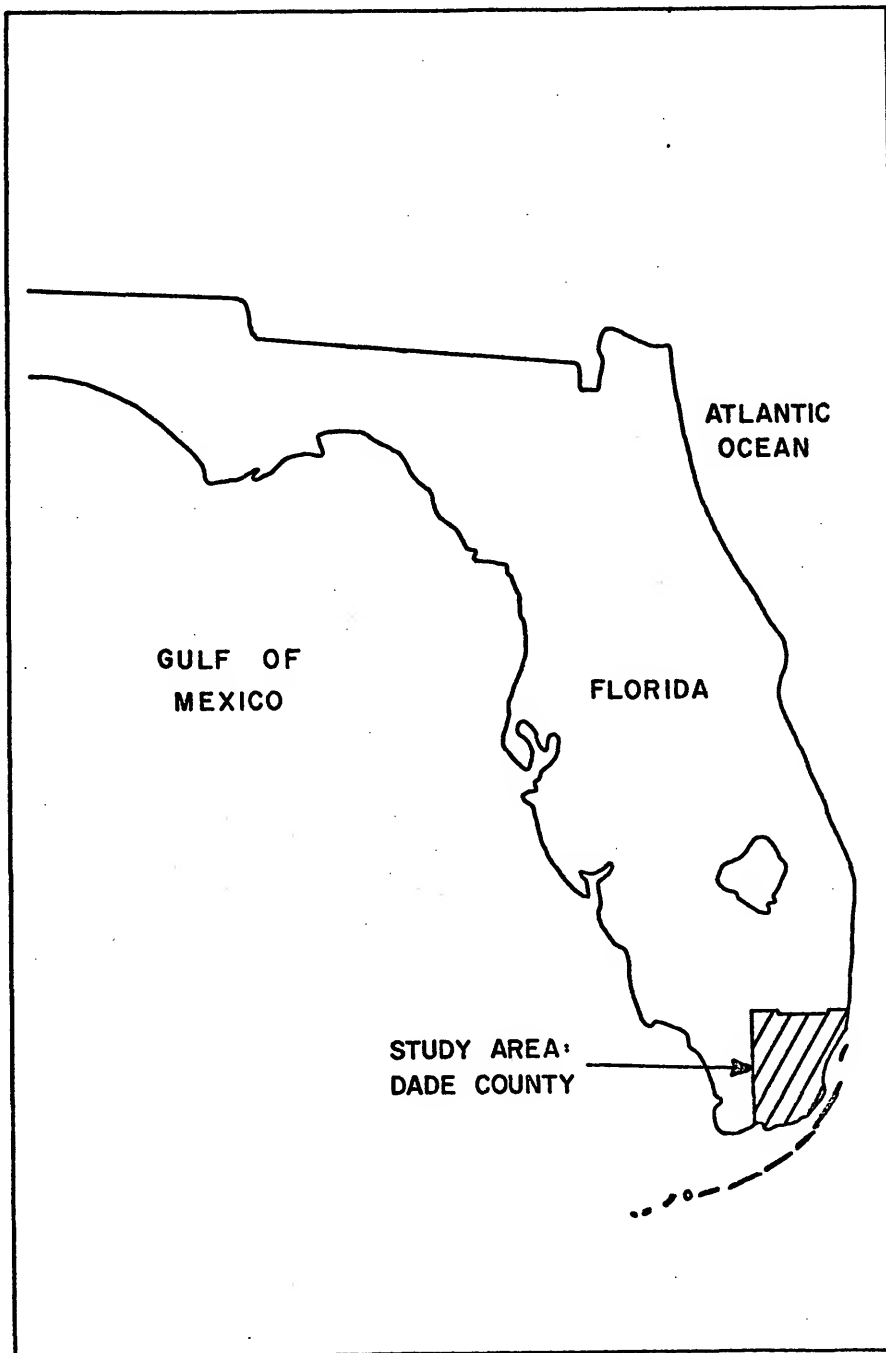
subtropical ecosystems, sea breezes and moderate temperatures maintained by the offshore Gulf Stream. Summer temperatures average 81°F, winter temperatures 61°F, relative humidity is usually between 50 and 85, and 60 inches of rain fall per year. The additional diversity of luxury hotels coupled with the natural systems acted as a magnet for tourism and money income. Up until recently tourism was the main source of income with some 10 million tourists visiting the county in 1973. In recent years the economy diversified with light industry and aircraft related businesses, and Miami has become a major embarkation point to Latin America and Europe. Manufacturing plant employment increased from 29,000 in 1954 to 77,000 in 1970.

The northern portion of the county is heavily urbanized (>10 persons per acre) with this urbanization continuing northward into Broward and Palm Beach Counties; this developed coastal strip is known as the Gold Coast. Miami Beach is an island off the east coast, world famous, and intensely developed with large, high-rise hotels and apartments. The major means of transportation is the automobile with the Palmetto expressway, I-95, U.S. 1, and Old Cutler Road acting as main arteries through the region. As in most other large American cities there are concentrations of poor people in and around the downtown area with high crime rates, low income, and substandard housing. The average income level is higher in the southwest and southern portions of the developed area and is characterized by modern, single family residences. Urban

development has proceeded southward, influenced directly by southbound U.S. 1. Growth is also taking place about Homestead and these two urbanized areas are creeping toward each other along the U.S. 1 route. The western and southern portions of the county are covered by extensive areas of marsh grasses with intermittent hardwood hammocks and cypress domes. The county is also covered by 238×10^6 sq. meters (59,000 acres) of agricultural land, tomatoes being a principal crop. Along the southern and eastern coasts are systems of mangrove trees. The major power station is located at Turkey Point.

The southern portion of Florida has long had plentiful quantities of water during the rainy season with large sheet flows occurring from areas north of the county near Lake Okeechobee to the southwestern and southern shores of Dade County. These large flows of water occur mainly along the Shark river slough. The county is also underlain by an extensive, shallow fresh water aquifer known as the Biscayne aquifer, 1,500 square miles of which lie within Dade County. Approximately 38 inches of rainfall passes through the Dade County portion of the aquifer, which is approximately 2.72×10^9 gallons per day. This aquifer is the result of extensive formations of permeable limestone rock; this rock is the only mineral resource in the county. The county is also underlain by a deep aquifer (approximately 800 feet deep) of brackish and salt water known as the Floridian aquifer, which is separated from the Biscayne aquifer by a layer of impermeable rock. In an attempt to control floods, manage water supplies,

and develop agriculture and urban areas the Federal govern-
ment has created an extensive system of canals, levees, dams
and pumps to regulate water flow. The canals prevent flood-
ing by passing water quickly to the sea, but this lowers the
water table, increasing the chances for salt-water intrusion.
Local pumping near the coastline has also increased salt-
water intrusion. The majority of water that used to flow to
the Everglades has been diverted, a major reason for the
extensive decline in that ecosystem. This system of man-made
water control structures has radically changed the makeup of
the county. Biscayne Bay borders the county on the east and
pulse discharges of water from the canals stress this aquatic
habitat.

The population of Dade County in 1973 was approximately
1.3 million, starting from a mere seventeen hundred people in
1900 and net in-migration was approximately 40,000 people per
year. There were large migrations of Cubans in the late
1950's and early 1960's because of the Cuban revolution.
They migrated into the downtown area and the approximately
300,000 Spanish-speaking residents of the county, 200,000 of
whom are Cuban, give it a distinctly Spanish flavor. Migra-
tions of blacks from the rural areas have resulted in 189,000
blacks living mainly in the downtown areas. Politically, the
county consists of 27 municipalities which were incorporated
in 1957 under the Metropolitan Dade County Government, while
40% of the population still lives in unincorporated areas of
the county.

Review of Previous Miami Studies

There have been many reports compiled dealing with the economic, historical, physical, and social aspects of the Miami-Dade region. The following paragraphs summarize many of the reports which have been published dealing mainly with the economic and physical aspects.

The Metropolitan Dade County Economic Survey (November, 1970) gives a brief review of the economic and social state of Dade County including statistics on business, climate, health, education, economic indicators, transportation, utilities, population and services. It focuses on the attractive aspects in order to encourage business and people to migrate into the county. The report, "Profile of Metropolitan Dade County: Conditions and Needs" (Goode, 1972), is a compilation of spatial and temporal data for population, environment, economy, housing, health, education, leisure time, public safety, transportation and social services. The report contains well-illustrated maps depicting such things as racial distributions, transportation systems, incidence of disease, parks, incidence of crime, environmental quality index, and other parameters. The report, "Facts and Figures Show How DADE DOES IT RIGHT" (1972), put out by the Miami-Metro Department of Publicity and Tourism is a compilation of information showing employment, income, indebtedness, budgets and several indicators of growth which are supposed to indicate the viability, attractiveness and growth potential of the region. Greeley

and Hansen (1972) evaluated fifteen wastewater disposal plans
and recommended construction plans for wastewater treatment
facilities based on projected population growth. Hartwell
et al. (1973) summarized the limits of water availability to
Dade County and attempted to show in a general way the stress
of increasing population on the water supply and other parts
of the system. Studies by Klein (1957,1965,1971), Kohout and
Klein (1967), Meyer and Hull (1967), Hull and Galliher (1970),
Galliher and Hull (1969), Parker et al. (1944) and Leach and
Grantham (1966) deal with hydrological conditions and the
effects of water discharge and pumping on various areas of the
county. Salt water intrusion is mapped as is fresh water head.
Road and expressway development plans for midtown Miami based
on anticipated growth are contained in "Multiple Use Opportun-
ities for Midtown Miami" (1971). Several ecological studies
of specific systems within Dade County have been completed by
Bader and Roessler (1972), Wilson (1973), and McCoy (1973).
These studies dealt with Biscayne Bay, soil arthropods, and
algal mats. The Dade County Economic Base Study (1960) ana-
lyzes Dade County's personal income position. For a develop-
ment just north of Dade County, Veri (1972) tried to assess
the impact of the development on the surrounding area, a small-
scale systems approach. It was concluded that the impact on
the existing neighborhood would be undesirable and that popu-
lation increases in the region should be greatly curtailed.

Several investigators have attempted to look at the
problems of South Florida and Dade County in a holistic or

interdisciplinary fashion. Marshall (1972) discusses the
carrying capacity of South Florida and the interaction and
interdependence between the Everglades and the Gold Coast.
The implication is that the South Florida system is already
overtaxed and as the Everglades goes, so goes South Florida.
Buchanan (1973) in the RALI report has provided a sampling of
information for 1,800 square miles in the southern part of
Dade County which should help in creating solutions for repre-
sentative problems in the county. This report seems to focus
on the technological alternatives which are necessary to pro-
vide the services needed for an expanding population. First
Research Corporation (1973) conducted economic studies for
the state of Florida by dividing the state into five market
areas. One of these areas included Dade and Broward Counties,
containing the area known as the Gold Coast, a strip running
along the coast. This study attempted to predict future mar-
ket demand by projecting past population and economic growth
into the future and thus predicting demand. No effect of out-
side energy and inflationary pressures was included in this
analysis.

Summary of Urban Modeling Approaches

While this dissertation emphasizes an energetic-ecological
approach to urban systems there are other modeling approaches
which have been applied. The following paragraphs briefly
describe some approaches used by other investigators.

Economic-Demographic Models

Economic based models. The external sector is the exclusive generator of growth with an assumed linear relationship between the level of external activity and that of local activity. Growth depends on external demand and supply factors are disregarded. No consideration is given to available energy (Yujnovsky, 1972).

Income expenditure models. Aggregates of components in the economy are defined based on sources of regional income and product. This goes a step beyond the previous model in that local demand is considered. There are extensive data requirements and field research necessary. For example,

$$V + M = C + I + G + X$$

where V = regional product,

M = imports,

C = regional consumption,

I = regional investment,

G = regional government expenditures, and

X = regional exports.

The method still lacks supply or available energy considerations (Yujnovsky, 1972).

Input-output analysis. Disaggregates the economy into n sectors so that production of one sector can be expressed by means of

$$X_i = \sum_{j=1}^{n} X_{ij} + Y_i \qquad (i = 1, 2, \ldots n)$$

where X_i = total production of sector i,

X_{ij} = production of sector i to be used as input to sector j, and

Y_i = final demand.

Now, $X_{ij} = A_{ij}X_j$

where A_{ij} is the input-output coefficient as the minimal input required to produce a unit of a particular output. Substituting

$$x = Ax + y \qquad \text{(matrix)}$$
$$x = (I-A)^{-1} y$$

which is a set of linear, simultaneous equations. Basically, it is an accounting scheme to keep track of the interdependence of different sectors of the economy and is applicable for a system in equilibrium or for small changes about the reference or nominal systems.

Programming models. These consist of linear equations for which some objective function is met such as maximizing net income or minimizing the total cost of the use of resources. The market is defined in advance as a set of fixed prices for all consumption goods (Yujnovsky, 1972).

Simulation. Attempts to take into account the complex interdependence, feedbacks and non-linearity of social systems. It is assumed that the levels and rates of change of a set of components describe the state and changes of the system (Forrester, 1971). These models are usually not spatial in character although they could be used as such.

Demographic models. Population prediction models which have socio-economic variables as important parameters. The phenomenon of migration is poorly understood and usually jobs are used as a main attraction. Gravity, diffusion and probability models have been used to describe migration (Yujnovsky, 1972). This is probably where energy available to urban and agricultural regions should be considered.

Spatial Distribution Models

Location theory. Revolves about the theory that the location of a city will coincide with the least transport cost location with respect to the source and market of raw materials.

Central place theory. Central place refers to the location of a city as an area performing retail and service functions for surrounding areas. The two results of this theory are that the area served increases exponentially with the population size of the center and that the total number of establishments varies exponentially with both population size of center and total population densities (Berry, 1964).

Rent theory. Each activity in the urban area minimizes the sum of rent and transportation costs. Various schemes are developed for trade-offs between these costs and expressions are assumed for these costs as functions of distance (Yujnovsky, 1972).

Gravity models. Distributes residential population by relating places of residence to places of employment and

allocates service activity by relating its employment to the spatial distribution of population. The number of trips between two areas i and j is given by

$$V_{ij} = V_i \sum_k \frac{A_i d_{ij}^{-b}}{A_k d_{ik}^{-b}}$$

where V_i = total number of trips generated at i,

$\quad d_{ik}$ = measure of distance between zones i and k, and

$\quad A = $ = a constant.

Transportation and trip generation models. These models are concerned with trip generation as a function of socio-economic variables, trip distribution, choices among differ-ent modes of transportation, estimates of travel demand and predictions of traffic volume at both micro-macro and inter-intra urban levels (Yujnovsky, 1972).

Ekistics. The term ekistics has been used extensively by Doxiadis (1963) and means the study of human settlements. Doxiadis, an architect, has chosen to look at the general spatial patterns of cities from an historical, cultural and functional point of view. Unlike most of the previous approaches mentioned above, Doxiadis chooses to rely more on intuitive judgment when trying to design a functional pattern to meet human needs. In particular, his consulting firm has proposed a transportation network and master plan for down-town Miami which relies heavily on the automobile although it has provision for the implementation of a mass transit scheme

(Doxiadis Associates, Inc., 1967). Ekistics could also be considered a holistic approach to city spatial planning.

System or Holistic Urban Models

Although the models described above have been viewed as presenting explanations of various aspects of urban systems, they all are restricted to limited parts of the city, e.g., transportation. They also suffer from an economic viewpoint of the world without consideration of some of the basic biologic-energetic laws which drive and limit natural systems and which, theoretically, are an integral part of urban systems. For the most part, use is made of linear equations for description since the techniques for the solution of linear equations are well established. The following paragraphs describe models or views of the world from a macro-system point of view in an attempt to pick out the important variables of the city, connect them into a system, and pick out some important principles which can be used to make judgments about city properties and behavior.

General system theory. It has been recognized that cities or urban areas define operating systems with interlocking parts which exhibit certain properties and perhaps obey several general laws of system behavior. Built into these system approaches may be economic, social, ecological, etc., biases. One of the distinct advantages of a general system approach is that it is not restricted to a particular field of study or a linear description of the system.

Energetic-ecological approach. Several investigators have attempted to look at several aspects of urban and human systems in terms of biological, energetic and ecological points of view deriving from the vast knowledge that has been compiled on the workings of natural systems in order to understand man and his systems, even though they are influenced in as yet unexplained cultural ways. H. T. Odum (1971) applies energy concepts and systems thinking to the systems of man and much of this approach is incorporated in this dissertation. Holling (1969) outlines the similarities between ecosystems and social systems with special reference to ecological stability. A predator-prey model is used to model land development where land acquisition is analogous to predation.

In Ian McHarg's book Design with Nature an approach is presented which attempts to combine the various properties of an area, e.g., physiography, geology, hydrology, plant associations, historical value, etc., in a systematic way in order to develop in optimum locations. Maps are created of each property indicating its value (based on a scale of 1 to 10, for example) by means of shading from black to clear. All of the maps are then overlaid and the areas which come out the darkest (or lightest, depending on the reference) are considered most suitable for development. The technique suffers from the fact that each property is assumed to be independent and if any weighting factor is used it is up to the investigator to make value judgments among the different properties. This approach is an admirable technique for trying to bring

together and unite the systems of man and nature in a spatial
way--no calculations are made of energetic value. Essentially,
it is an architect's ecologically oriented attempt at planning
which needs to have a quantitative theory wedded to it.

METHODS

Description of Modeling Language

All symbols used in the model diagrams have been estab-
lished by H. T. Odum in the development of his energy lan-
guage. A description, explanation and mathematical descrip-
tion of these symbols can be found in Odum (1971,1972). The
symbols used in this thesis are summarized in Fig. 3.

Model Development

Based on previous modeling experience, urban studies,
ecological principles, energetic concepts, and discussions
with various people, preliminary models are constructed with
the aid of the symbols described in Fig. 3. A pictured repre-
sentation has advantages over mathematical equations in that
it allows one to identify interactions more easily. A list
of the major outside forcing functions is compiled along with
the major storages (state variables) within the system. The
topological structure of the model is then created by making
assumptions about the interactions between the outside sources
and the internal storages. This determines the pathways
entering, leaving and internal to the system. The conceptual-
ization of the model also aided in the data gathering process

Fig. 3. The symbols of the energy circuit language used
in this dissertation (Odum, 1971,1972).

    a. Outside source of energy supply to the system
controlled from outside; a forcing function
(E).

    b. Constant flow source from outside;
$J_2 = k_2 J_0 X/(k_r + k_1 X)$, $J_r = k_r J_0$, $J_1 = k_1 X J_0$.

    c. A pathway whose flow is proportional to the
quantity in the storage or source upstream
$(J = k_1 E)$. The heat sink represents the
energy losses associated with friction and
backforces along pathways of energy flow.

    d. Storage of some quantity in the system.
The rate of change equals inflows minus
outflows $(\dot{Q} = J - kQ)$.

    e. Interaction of two flows to produce an out-
flow which is some function of these flows;
usually a multiplicative output, i.e.,
$f(X,Y) = kXY$.

    f. Transactor symbol for which money flows in
one direction and energy or matter in the
other direction with price (P) adjusting
one flow (J_1) in proportion to the other,
$J_2 (J_1 = PJ_2)$.

    g. A combination of "active storage" and a
"multiplier" by which potential energy
stored in one or more sites in a subsystem
is fed back to do work on the successful
processing and work of that unit; auto-
catalytic.

    h. Production and regeneration module (P-R)
formed by combining a cycling receptor
module, a self-maintaining module which it
feeds, and a feedback loop which controls
the inflow process by multiplicative and
limiting actions, e.g., the green plant.

    i. Sensor of the magnitude of flow, J.

27
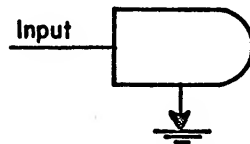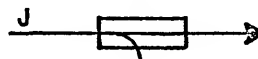
by helping to identify important pathways. Numerical data were then compiled from the literature for the various storages, pathways and outside sources. Some of the data were approximated by using state or national average per capita data.

Data Assembly and Evaluation

Collection and Organization

By going to city agencies in Miami, state agencies in Tallahassee, and searching library reports and documents, a library of reports was gathered containing information on the urban system of Miami-Dade County. Data on such things as total energy consumption, total budget, effective buying income, population, number of telephones, building structure, retail sales, taxes, water consumption and land development were collected, graphed and tabulated by year from 1950 to 1972. Data for all years were not always available so that the most recent values found were used in the models and calculations. The consumption of fossil fuels such as natural gas and liquid fuels was estimated based on values for the state (Minerals Yearbook, Mineral Industrial Surveys). A table of fossil fuel consumption for Florida from 1950-72 is contained in Appendix I. Total, per capita, and rates of change for the variables mentioned above are also contained in Appendix I. Graphs of the data plotted as a function of time and energy are contained in the Results section. Land

areas for urban and natural areas were obtained by planimetering maps (see Table 10) and aerial photographs (January, 1973).

Cross-Correlation Analysis

For two functions X and Y which are changing with time, it is sometimes desirable to know how well correlated in time these functions are. Correlation in this sense means how well two signals track each other in time. For example, if the two signals are ramps of equal slope they would be said to be well correlated; likewise, ramps of equal slope but of opposite sign would be negatively correlated. The cross-correlation function (see Lee, 1960) between two continuous signals, X and Y, is defined by

$$\phi_{XY}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} X(t)Y(t+\tau)\,dt$$

where the signals are considered over the interval $(-T,+T)$. The parameter τ is the shift in time between the two signals for which the cross-correlation function is calculated. Two sinusoidal functions of equal frequency and in phase would be strongly correlated. As these two signals were shifted in time they would become less correlated until they were completely out of phase. They would then be strongly negatively correlated. The correlation function can be normalized to obtain a correlation coefficient defined by

$$r_{XY}(\tau) = \frac{\phi_{XY}(\tau)}{\sigma_X \sigma_Y} \leq |1|$$

where $\quad \sigma_X = \sqrt{\phi_{XX}(0)}$

$\qquad \quad \sigma_Y = \sqrt{\phi_{YY}(0)}$.

If the two functions X and Y are not continuous but discrete values of the functions are known then the correlation function is defined by

$$\phi_{XY}(\tau) = \frac{1}{K} \sum_{i=1}^{K} X_i Y_{i+\tau}$$

where τ is the shift in time between the two functions X and Y and K is the number of data points. The correlation coefficient is defined as above.

If the two functions are both non-stationary (containing a trend) then one may not necessarily "cause" the other. For example, the increasing population of New York could be correlated to the increasing price of tea in China, even though they have no relationship to each other. For Miami-Dade County all variables have been increasing up until 1972. To avoid the non-stationary nature of the functions a cross-correlation analysis was done for the first differences (rate of change) of the various parameters to see if these correlated. This cross-correlation function is given by

$$\phi_{\Delta X - \Delta Y}(\tau) = \frac{1}{K} \sum_{i=1}^{K} \left(\frac{\Delta X}{\Delta t}\right)_i \left(\frac{\Delta Y}{\Delta t}\right)_{i+\tau}$$

and this equation was used to construct Table 2. $\Delta X/\Delta t$ and $\Delta Y/\Delta t$ represent the rates of change of X and Y. Again the correlation coefficient is defined as

$$r_{\Delta X - \Delta Y}(\tau) = \frac{\phi_{\Delta X - \Delta Y}(\tau)}{\sigma_{\Delta X}\sigma_{\Delta Y}}$$

where $\qquad \sigma_{\Delta X} = \sqrt{\phi_{\Delta X - \Delta X}(0)}$

$\qquad\qquad \sigma_{\Delta Y} = \sqrt{\phi_{\Delta Y - \Delta Y}(0)}$.

The program used to calculate the cross-correlation function is called CORR and is contained in the Nuclear Engineering Sciences computer center, University of Florida.

Simulation Procedure

Simulation Model

Although a very complex model containing many storages and pathways can ultimately be simulated on a digital computer, important results can be obtained by other methods. Simplifying complex models by lumping storages and eliminating small flows but maintaining the essence of the model allows analog simulation, reduces chances of error, and prevents the model from overwhelming the researcher with too much detail. After a suitable model is decided upon, the equations representing it are solved on an analog computer and output curves generated.

Writing, Scaling and Programming of Equations

Associated with each model diagram is a set of first order differential equations (N^{th} order system) which describe the rate of change of the state variables. The equations are obtained by setting the rate of change with time of a state variable equal to the inputs minus the outputs to that storage.

These pathway flows will be equal to some constant, K, times a product of state variables and sources. This coefficient can be calculated knowing the value of the flow and the state variables and sources. In order for the equations to be solved on the analog computer they must be scaled, i.e., the maximum value that a state variable will achieve should correspond to the maximum voltage output of the computer. For an example of scaled equations see the details of simulations in the appendices. An analog diagram is then drawn to represent the equations with each storage corresponding to an analog integrator. This diagram is then programmed on the computer for solution. The numerical coefficients in the differential equations are transformed into potentiometer settings on the analog computer. For example, given the equation

$$\dot{Q}_1 = .05 Q_1 Q_2 - .3 Q_1.$$

where $Q_{1max} = 10$ and $Q_{2max} = 10$. Then

$$\dot{Q}_1 = .05(10)(10)\left(\frac{Q_1}{Q_{1max}}\right)\left(\frac{Q_2}{Q_{2max}}\right) - .3(10)\left(\frac{Q_1}{Q_{1max}}\right)$$

where the ratios in brackets are now the scaled computer values and cannot exceed the maximum voltage of the computer since Q_{max} corresponds to the maximum voltage. The entire equation is then divided by Q_{1Max} in order to scale $\dot{Q}_1$ the same as Q_1. This means that one second of computer time will correspond to the unit of time which the real-world problem

is expressed in. If flows are expressed as per year then one second of computer time will represent one year. The equation resulting by dividing by $Q_{1Max} = 10$ is

$$\left(\frac{\dot{Q}_1}{Q_{1Max}}\right) = .05(10)\left(\frac{Q_1}{Q_{1Max}}\right)\left(\frac{Q_2}{Q_{2Max}}\right) - .3\left(\frac{Q_1}{Q_{1Max}}\right)$$

The coefficient of the product $[Q_1][Q_2]$ is equal to .5 and is the value that a potentiometer will be set at. Likewise, the potentiometer setting for the last term is .3.

Energy-Economic Budget Calculations

Since there are no money flows in nature a method by which natural and man-made systems can be compared is to use energy flow as a measure of useful work. The gross production of natural vegetation can be estimated and used as a measure of the useful work necessary to maintain a given ecosystem. The work performed by the natural energies of wind, waves, and tides can also be calculated. Work processes in man-made systems can be measured by fossil fuel and money flows. In order to compare the energy flows associated with natural and man-made systems, a common unit of energy is necessary which measures equal ability to do useful work. For example, how much work can 1 Kcal of sunlight do compared to 1 Kcal of coal.

Energy Concentration Factor and
Energy Value of Money

Consider Fig. 4a, which is a simplified diagram of the process of converting coal into electricity (Lem, 1973). The box represents a power plant which is driven by inputs of coal and purchased goods and services. The dollar value of goods and services has been converted to Fossil Fuel Work Equivalents[1] by using the conversion factor of 25,000 Kcal/ dollar (Odum, 1974a). This ratio has been obtained by taking the ratio of total sunlight falling on the United States per year (in Fossil Fuel Work Equivalents, FFWE) plus the fossil fuel used per year and dividing by the Gross National Product of the U.S. This ratio is a measure of the fossil fuel work that one dollar can generate in the economy. There is some disagreement as to the magnitude of the dollar to kilocalorie ratio. Kylstra (1974) has calculated the ratio from 1947 to 1972 with the ratio in 1972 about 22,000 Kcal/dollar. The natural energies included in this calculation did not include the offshore marine productivities so that the ratio may be somewhat higher. The natural energies were calculated by taking the solar energy falling on the United States and con- verting to FFWE's by dividing by 2,000. The actual value is probably somewhere between 22,000 and 25,000 Kcal/dollar for 1972. This energy to dollar ratio has been steadily decreas- ing since 1947 so that the approximate figure of 25,000 Kcal/

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[1]A Fossil Fuel Work Equivalent (FFWE) is the amount of useful work that 1 Kcal of fossil fuel is capable of doing.

Fig. 4. Examples illustrating the concept of energy
quality. (From H. T. Odum, unpublished papers.)

    a.   Diagram showing major inputs necessary
to generate electricity and upgrade energy
concentration (quality). It is seen that
1 Kcal of electricity is generated from
approximately 4 Kcal of fossil fuel inputs.

    b.   Energy chain showing the upgrading of
energy from dilute solar energy to con-
centrated electrical energy. Boxes
represent energy conversion processes.
Numbers in parentheses are energy concen-
tration factors showing the number of
Kcal of energy needed to generate 1 Kcal
of electricity.

36

Purchased Goods
and Services

5.9×10^{12} kcal

Coal

14.9×10^{12} kcal

Power
Plant

5.65×10^{12} kcal
Electricity

$$\frac{14.9 + 5.9}{5.65} = 3.7$$

(a)

Sunlight

Organic
Matter

Coal

Electricity

(8000)

(80)

(4)

(1)
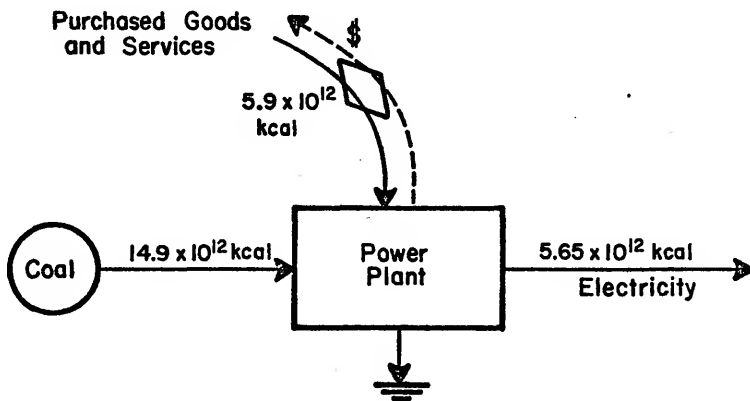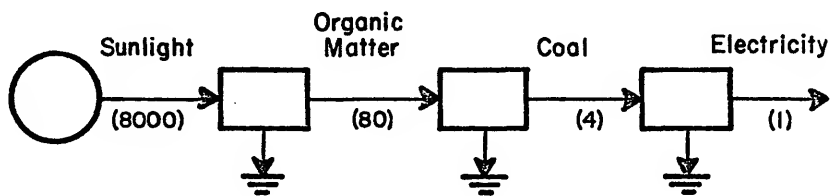
(b)

dollar will introduce some error into several calculations.
Since the conversion of natural energies to FFWE is also
approximate, the value of 25,000 Kcal/dollar should suffice
as a reasonable approximation. This number is an average
value for dollar flows of goods and services which have been
affected by many sectors of the economy. It can be seen from
Fig. 4 that the ratio of the Kcal value of fossil fuel inputs
to the Kcal value of the electrical output is 4. In the
process coal has been upgraded to a higher quality and more
versatile form form of energy, namely, electricity. Four
Kcal units of coal are necessary to produce one Kcal of elec-
tricity. It is said that the fossil fuel work equivalent of
electricity is four, or that the energy concentration factor
of electricity relative to coal is four.

This same concept can be applied to other forms of
energy such as sunlight and organic matter by consideration
of the chain of energy processes necessary to go from sun-
light to electricity. Figure 4b diagrams in simple form the
energy conversions between sunlight and electricity. Tenta-
tive energy concentration factors for several types of energy
are listed in Table 1. Dividing a given type of energy flow
by this factor will give the energy available in Fossil Fuel
Work Equivalents. This concept of energy concentration
(quality) is in a theoretical phase following from the idea
that energy storages must be of an upgraded higher quality.
Lotka's principle also requires that energy must be upgraded
and stored to accelerate inflow and effective use. The

Table 1

Energy Quality (Concentration) Factors
Relating Different Work Processes

Energy Conversion Process	Energy Quality (Concentration) Factor[a]
Sunlight to Gross Production	100
Gross Production to Wood	10
Wood to Fossil Fuel	2
Wood to Electricity	8
Gross Production to Fossil Fuel	20
Sunlight to Fossil Fuel	2000
Tidal Energy to Fossil Fuel	0.3
Hydrostatic Head to Fossil Fuel	0.3
Fresh/Salt Water Concentration Gradient to Fossil Fuel	10(?)
Total Work Done in U.S. per Dollar	25000 Kcal/Dollar

[a]The Energy Quality Factor is a ratio of total energy inputs (including all subsidies) to energy output from the conversion process. By using appropriate sets of ratios, different forms of work can be converted to the same equivalent type and then compared or summed. Energy Quality Factors are preliminary and subject to readjustments. See Odum (1974a), Kemp (1974), Young et al. (1974), and Costanza (1975).

numbers in Table 1 should be considered approximate and pre-
liminary.

Theoretically, then, all energy flows of man and nature
can be compared by reducing them to the same common denomi-
nator of FFWE's. Likewise, the money flows of human systems
can be interpreted as the work they require in the economy
by the conversion factor of 25,000 Kcal/dollar (Kcal of
fossil fuel work). Thus, all the work contributions of man
and nature can be compared on an equal basis (see Table 11).

RESULTS

Data on Miami-Dade County

     In this section data are assembled from many sources
for combination in energy models toward understanding the
urban system. One of the most difficult aspects of under-
standing cities in terms of an energy framework is getting
data in energy units. In human systems the standard unit of
measure is money and most data are in dollars. However, for
every dollar flow in the economy there is an exchange of goods
and services. These goods and services were the net result
of the accumulation of processes in the economy which were
dependent on energy support. In effect, a dollar can buy a
number of kilocalories of useful work which was done in the
general economy (see Methods; Odum, 1971). Dollar statistics
give some indication of the energy intensity of the systems
which they characterize. For example, the budget of a city
is representative of the energy going into maintenance of
those parts of the city considered public domain. Data were
compiled by referring to many of the publications listed in
the references (Dade County Economic Base Study, 1960; Dade
County Budget; Existing Land Use Study, 1961; Economic Survey
of Dade County, 1970; Dade Does It Right, 1972; see Table 6)
and constructing the graphs over time given in Figs. 5-11.

The numerical data for each year used to construct these
graphs are presented in Tables 20 to 21 in Appendix I with
notes explaining the numbers. The graphs were constructed by
connecting successive data points with straight lines. There
was one data point for each year. Data points are not shown
on the graphs for purposes of simplification.

Energy data for gasoline and electrical consumption were
obtained from publications of the Department of Transportation
and Metropolitan Dade County agencies. Numbers for natural
gas, residual and distillate fuel, kerosene and liquid petro-
leum were based on Florida consumption of these fuels as
listed in the Minerals Yearbook and Mineral Industrial Surveys.
Figure 5 presents gasoline consumption and total energy con-
sumption where total energy is the sum of gasoline, natural
gas, distillate and residual fuel, kerosene, liquid petroleum
and four times the electrical energy as explained in the notes
to Tables 19 and 20. This energy is expressed in Kcal of
fossil fuel. Population figures are shown in Fig. 6, water
consumption in Fig. 7, total budget in Fig. 8, dollar flows
in Fig. 9, number of telephones in Fig. 10, number of vehicles
in Fig. 11, and building structure in Figs. 10 and 11. One
of the most difficult parameters to find information for is
physical growth of a city, either in terms of square feet or
mass. Figure 11b was constructed by using the financial data
available for new construction each year and dividing by the
average cost per square foot ($8.50/ft^2).

Trends and Peculiarities

Looking at the data plotted in Figs. 5-11 it is seen that the trends are similar to those experienced in the rest of the country during a time of expanding energy, i.e., continual growth from 1950-72, except for a period during the late fifties and early sixties. If the rates of change for these parameters are looked at in Figs. 16-18 it is seen that the rates of change for total energy, effective buying income, sales tax, budget, and number of telephones have been increasing, indicating a power function for the growth of these parameters. The rates of change for water consumption, labor force, and population seem to have oscillated. Perhaps this is because these variables are subject to the random influence of weather and migrations.

There seems to have been fairly gradual growth from 1950 to about 1967 with the latter part of the sixties and early seventies characterized by rapid and accelerated growth. The birth rate (Fig. 6a) has been steadily declining since reaching a high in 1958 and the total increase in population seems to be following an oscillating curve due to migrations (Fig. 6b). It is interesting that several of the curves leveled for several years from the late fifties to the early sixties. During this period of time there were two large migrations of Cubans and the Miami Metropolitan government was created. The influx of Cubans brought in capital and created a larger tax base which may explain why the budget and sales tax leveled. There may have also been greater

Fig. 5. Fossil fuel energy consumption for Dade County.

      a. Graph of total and per capita gasoline
          sales in Dade County from 1950-72.

      b. Total and per capita fossil fuel con-
          sumption including natural gas, liquid
          fuels, and electrical energy from
          1950-72.
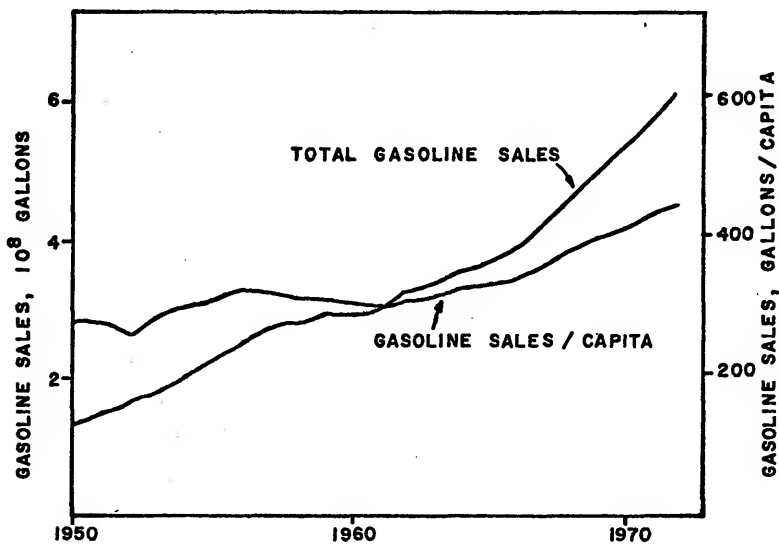
(a)
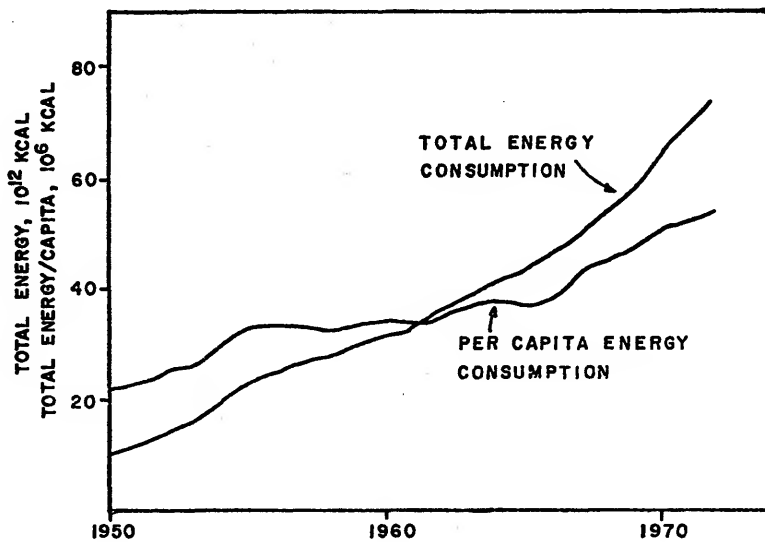
(b)

Fig. 6. Population statistics for Dade County.

        a.   Total population and births (natural
              increase) per year for Dade County
              from 1950-72.

        b.   Net migration and total increase in
              population for Dade County from
              1950-72.
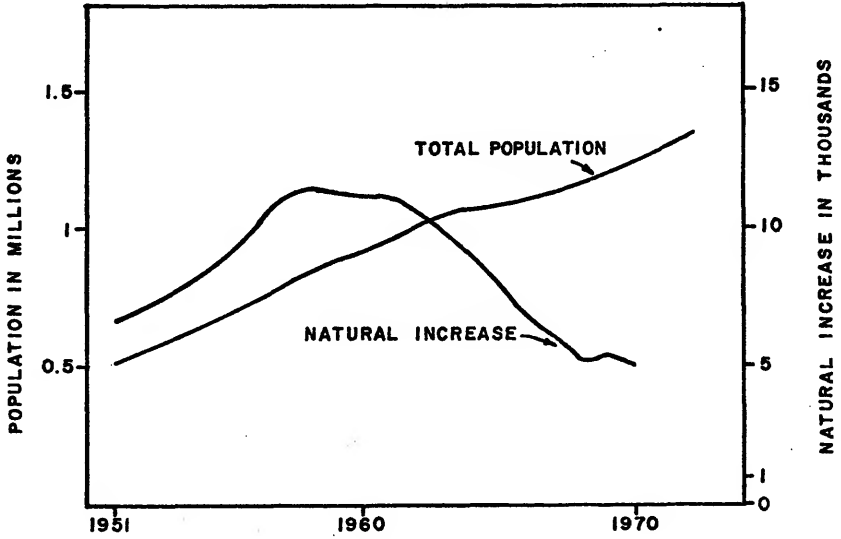
(a)
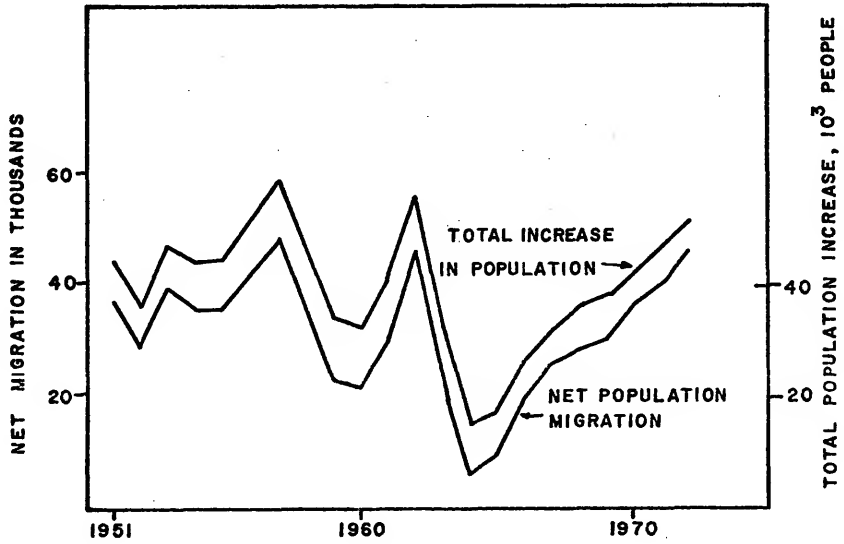
(b)

Fig. 7.   Total and per capita water consumption for
          Dade County from 1950-72.

Fig. 8.   Total and per capita budget for Dade County
          from 1950-72.
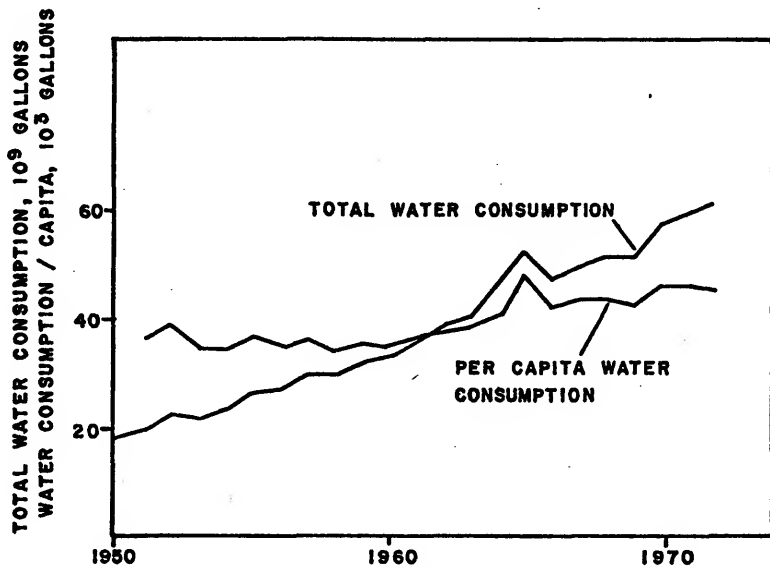
Fig. 7
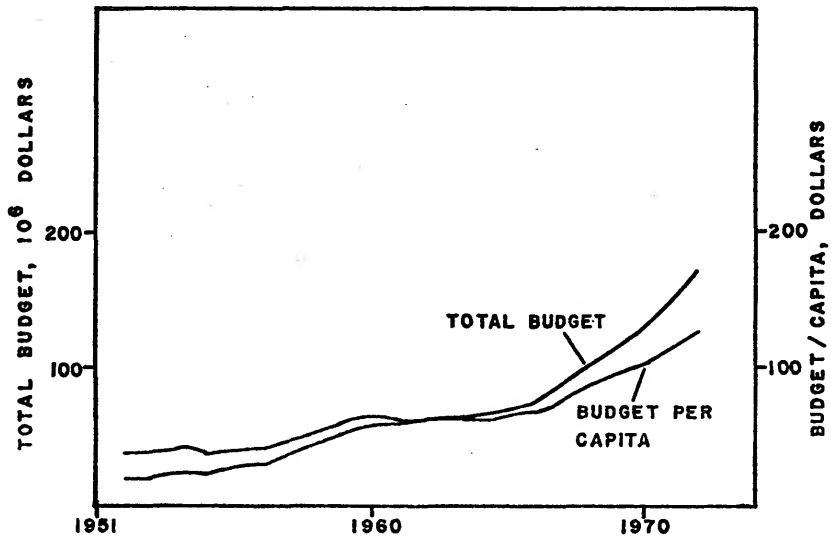
Fig. 8

Fig. 9. Economic measures for Dade County.

      a.   Total and per capita retail sales and
           sales tax collections for Dade County
           from 1950-72.

      b.   Total and per capita effective buying
           income for Dade County from 1950-72.

(a)

(b)
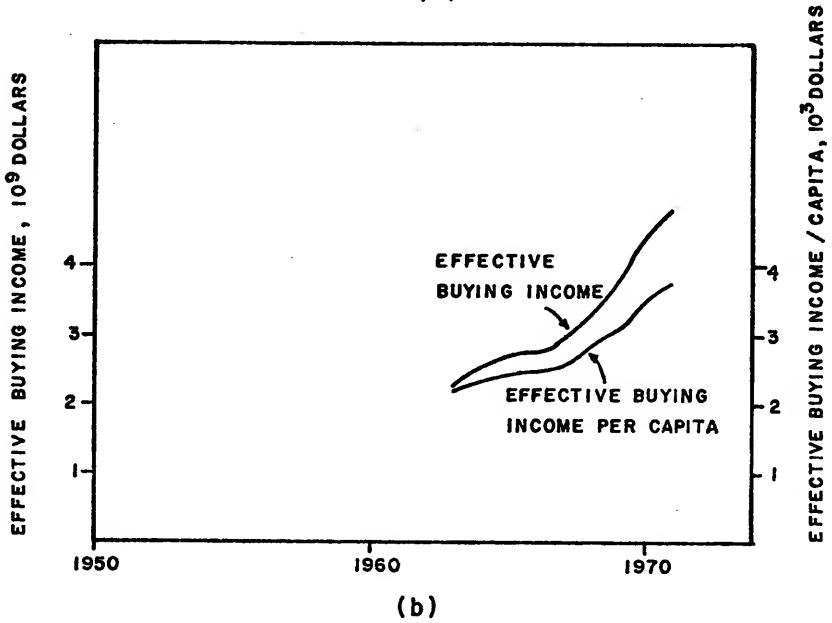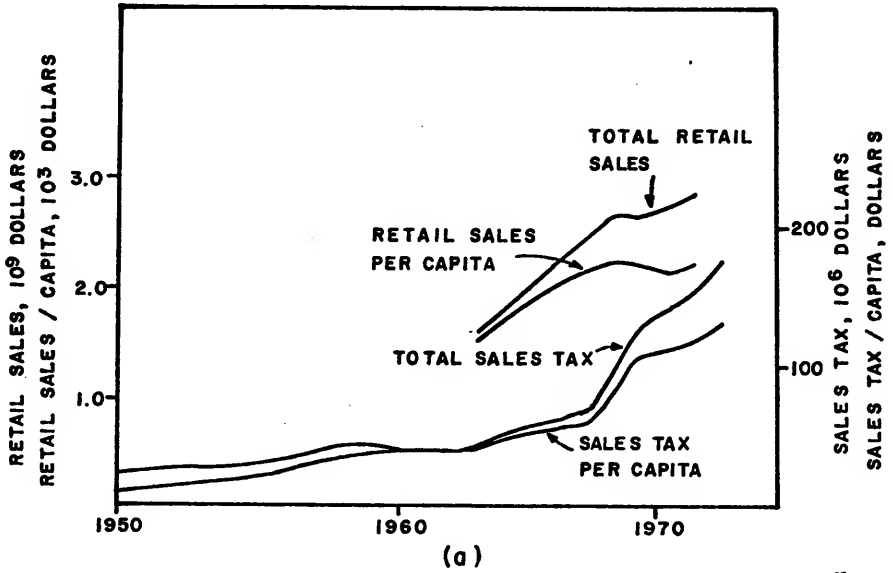
Fig. 10. Measures of structure for Dade County.

        a. Total and per capita value of building
              permits for Dade County from 1950-72.

        b. Total and per capita number of tele-
              phones for Dade County from 1950-72.

(a)

(b)
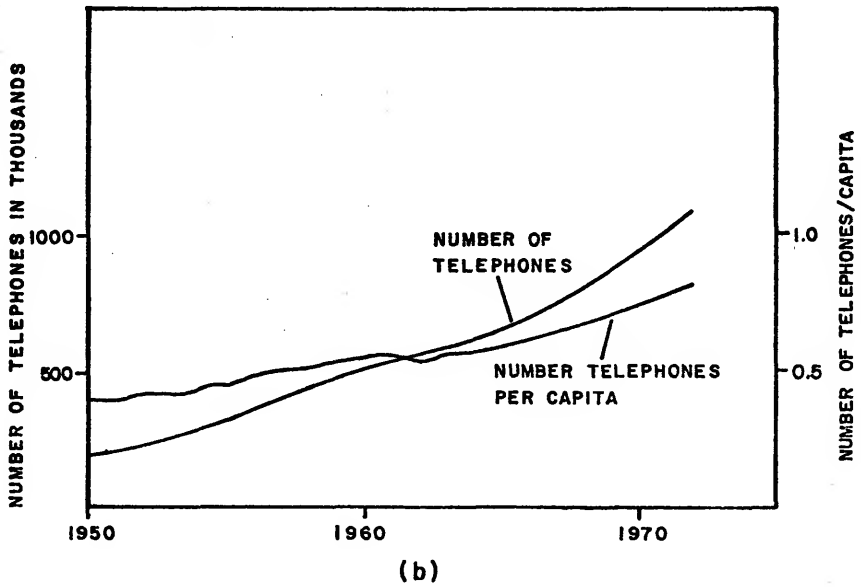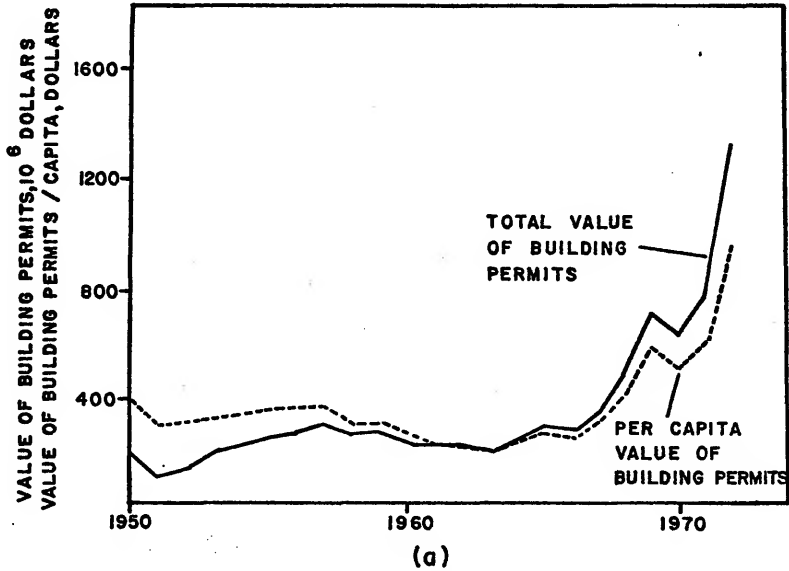
Fig. 11. Measures of structure for Dade County.

        a. Number of vehicles (autos, buses, and
            trucks) for Dade County from 1950-72
            in millions.

        b. Approximate total building structure
            for Dade County from 1950-72 in millions
            of square feet.
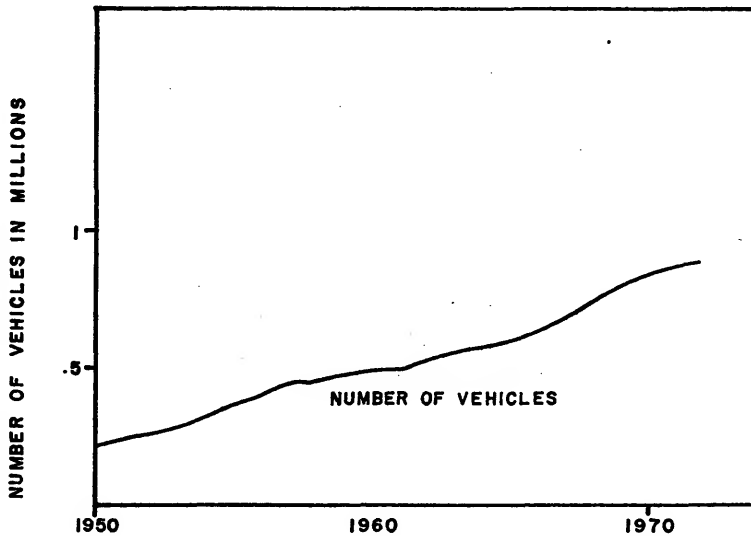
(a)
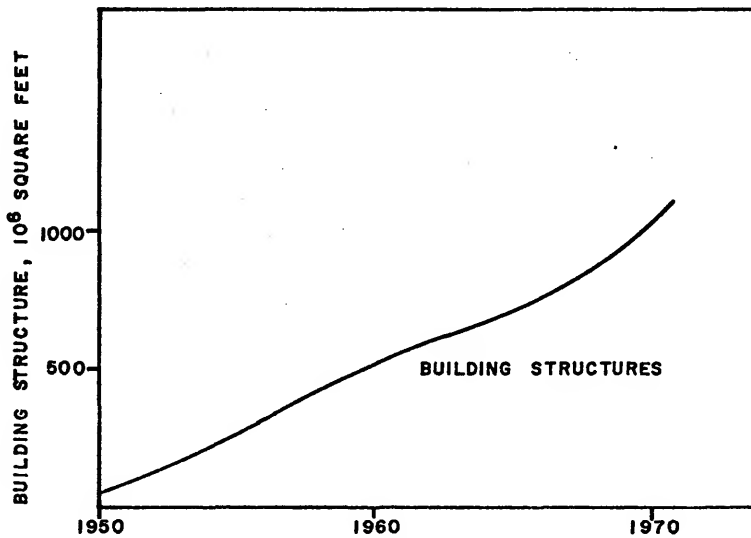
(b)

efficiency introduced due to the consolidation of the many separate municipalities.

Cross-Correlation Analysis

Cross-correlation analysis was performed for the time series data presented in the previous section. This type of analysis gives a measure of how well two functions track each other in time. It is usually important to determine the causal variable which the other variables in a system follow. For a city or any complex system it is sometimes difficult to determine which is the cause and what are the effects. Based on thermodynamic considerations energy seems to be a necessary and primal variable for urban systems. However, once a city system is established, changes in the population or money supply could also be construed as causal actions, at least over a short period of time. Eventually, energy and resources would become the primal cause. This section attempts to give some measure to the relationship of energy and population to several urban indicators.

Since most of the data have increasing trends (non-stationary) the first differences (yearly changes) were cross-correlated (see Methods). First differences of the variables are presented in Figs. 16 to 18. The cross-correlation function used can be found in the Methods section on page 30. Table 2 presents calculated values of the cross-correlation coefficient between first differences. First differences for population and total energy were cross-correlated with the

first differences of other urban variables. The greater the
correlation between variables the closer the correlation
coefficient is to one. Figures 16 to 18 show how many data
points were used for each of the correlations since one data
point was associated with each year. As can be seen from
Table 2, total energy and population rates of change corre-
late quite well with changes in other variables except for
water consumption and retail sales. The reason for the
retail sales negative correlation is unknown while that of
water consumption may be related to random effects of weather.

To put in perspective the change in energy consumption
compared to that of other parameters, Table 3 was constructed
to compare the percentage difference between 1962 and 1972
values for the number of telephones, retail sales, effective
buying income, sales tax, total budget, population, building
structure, number of tourists and total energy. It can be
seen that a 77% increase in total fossil fuel energy has been
accompanied by a 107% increase in effective buying income, a
250% increase in sales tax, a 130% increase in the budget,
and a 100% increase in the number of tourists. The number of
telephones, retail sales, and building structure changes have
been about the same percentagewise as the change in energy
consumption. Total population increased by 23.5%.

Table 2

Cross-Correlation Coefficients Between
the First Differences for Selected Urban Indicators

First Differences Correlated[a]	Cross-Correlation Coefficient[b]
Population to Total Energy	0.93
Population to Water Consumption	-0.0062
Population to Total Budget	0.92
Population to Sales Tax	0.56
Population to Gasoline Consumption	0.901
Population to Effective Buying Income	0.69
Population to Retail Sales	-0.5
Population to Value of Building Permits	0.9
Population to Number of Telephones	0.92
Total Energy to Population	0.93
Total Energy to Water Consumption	-0.17
Total Energy to Total Budget	0.83
Total Energy to Sales Tax	0.65
Total Energy to Effective Buying Income	0.716
Total Energy to Retail Sales	-0.65
Total Energy to Value of Building Permits	0.79
Total Energy to Number of Telephones	0.85

[a] First differences of the variables shown in this column were correlated (see page 30 in Methods).

[b] Cross-correlation coefficient given by equations on page of Methods section. This coefficient is a measure of how well two functions track each other in time. The maximum value of the coefficient is one and indicates high correlation. The time shift, τ, between the two functions was equal to zero for the coefficients calculated for this table (see page 29 in Methods section).

Table 3

Percentage Difference Between 1963 and 1971
Values for Several Urban Parameters

Item	Percent Difference[a]
Total Energy	77.0
Number of Telephones	67.1
Retail Sales	78.5
Effective Buying Income	107.0
Sales Tax	250.0
Budget	130.0
Population	23.5
Building Structure	76.0
Number of Tourists	100.0

[a]Percent difference was calculated by subtracting the value in 1963 from the value in 1971 and dividing by the value in 1963. This was multiplied by 100 to convert to percent.

Urban Indicators

The description of an urban system requires numerical information for parameters which indicate the state of the system. Traditionally, such things as population, area, population density, labor force, number of jobs and economic information have been tabulated. Recently, since the increase in environmental awareness, measures of environmental health and pollution have been introduced. Such things as number of comfort days and rainfall indexes are used to indicate weather conditions. These measures are used to compare different urban systems and build models.

Several other measures are needed and may possibly replace some of the above-mentioned ones for some purposes. For example, energy density (total energy consumed/unit area) may give a more realistic picture of the intensity of urbanization than population density. As can be seen from Table 4 the energy density of the Miami-Dade urban area is 300 $Kcal/m^2$/day compared to a New York City value of 4,000 $Kcal/m^2$/day (Odum and Peterson, 1972). Anyone who has visited these two areas can perceive the difference in intensity of these cities. Energy density could also be used to classify different types of subsystems within the city (Wetterqvist et al.; Brown, 1973). Total energy use per capita is a succinct measure of the activity in the city; this parameter can reflect the economic vitality of a population in a city.

Although most cities don't contain many large natural ecosystems, they do contain parks, open spaces, and trees. The ratio of the gross photosynthesis of this vegetation to the total energy consumption is an indication of the level of development of the city and the support from free natural work. The productive energies of vegetation, the natural energies of winds, water, waves, and sun provide free work services in a region. The ratio of all natural energies (vegetation and physical) to total energy (fossil fuel) use is important and may be a measure of tourist competitiveness with other competing urban regions.

Other indicators of urban areas include number of telephones (a measure of the communication web), retail sales, effective buying income (income left after taxes), sales tax collections, water consumption, budget, number of vehicles, net migration, square feet of buildings built (measure of structure), total energy consumed, and money incomes and expenditures. Another interesting measure is the ratio of floor space area built to that of the urbanized area, i.e., the ratio of growth in the vertical direction to that in the horizontal direction. In Table 4 it is referred to as the vertical/horizontal growth ratio. This ratio is an indication of three-dimensional growth. Table 4 is a list of the main urban indicators used for Miami-Dade County with their numerical values for 1971 or 1972 (see Tables 20 and 21 in Appendix I and Table 11 for more complete information on these parameters).

Table 4

Urban Indicators

Item	Total for 1972	Per Capita for 1972
Budget[a]	$173x10^6$	$126
Developed Area[b]	260 mile^2	.00019 mile^2
Economic Subsidies[c]	$1.48x10^9$	$1080
Effective Buying Income[a]	$5x10^9$	$3722
Energy Density in Developed Area[d]	300 Kcal/m^2/day	
Expenditures[e]	$6.8x10^9$	$4964
Fossil Fuel Consumption[a]	$74x10^{12}$ Kcal	$53.8x10^6$ Kcal
Labor Force[a]	$643x10^3$	.47
Net Migration[a]	$47x10^3$	.034
Number of Telephones[a]	$1.093x10^6$	.814
Number of Vehicles[a]	$880x10^3$	.64
Population[a]	$1.37x10^6$	
Population Density in Developed Area[f]	$5.27x10^3$/mile^2	
Retail Sales[a]	$2.82x10^9$	$2183
Ratio of Total Natural Energies to Fossil Fuel Consumption[g]	0.25	
Sales Tax Collections[a]	$179x10^6$	$133
Structure Built in a Year[h]	$150x10^6$ ft^2	110 ft^2
Structure Existing[i]	$1100x10^6$ ft^2	800 ft^2
Total Natural Energies[j]	$18.9x10^{12}$ FFWE	
Vertical/Horizontal Growth Ratio[k]	0.365	
Water Consumption[a]	$60x10^9$ gal	$44.4x10^3$ gal

[a] These items can be found in the Data section by looking at the graphs of these variables. Values can also be found in Tables 20 and 21 in the Appendix.

[b] Planimetered from aerial photographs (see Table 10).

Footnotes to Table 4 - continued

^{c}Consists of transfer payments plus federal subsidies to agencies. See notes 6 and 7 to Table 6.

^{d}Calculated by taking total fossil fuel use and dividing by the developed area:

$$\text{Energy density} = \frac{73.63 \times 10^{12} \text{ Kcal/yr}}{260 \text{ mile}^2} \times \frac{1 \text{ mile}^2}{2.59 \times 10^6 \text{ m}^2}$$

$$\times \frac{1 \text{ year}}{365 \text{ days}}$$

$$\text{Energy density} = 300 \text{ Kcal/meter}^2/\text{day}$$

^{e}See Table 9.

^{f}Calculated by taking total population and dividing by developed area:

$$\text{Population density} = \frac{1.37 \times 10^6 \text{ people}}{260 \text{ mile}^2} = 5.27 \times 10^3/\text{mile}^2$$

^{g}See Table 11 for a list of productivities for the natural and developed areas. The total energy of the natural systems is 18.9×10^{12} FFWE. In units of chemical energy this would be 20 times as great or 275×10^{12} Kcal. The ratio of natural energies in FFWE to total fossil fuel consumption is $18.9/73.63 = .25$.

^{h}See note 22 to Table 6.

^{i}See note 23 to Table 6.

^{j}See Table 11. An FFWE is equivalent to 1 Kcal of fossil fuel.

^{k}This was calculated by taking the approximate growth in square feet of structure and dividing it by the increase in developed land area from 1960 to 1972. This is a measure of vertical vs. horizontal growth. Thus, the ratio from 1960 to 1972 was

$$\text{Vertical/horizontal growth ratio} =$$
$$= \frac{1110 \times 10^6 \text{ ft}^2 - 520 \times 10^6 \text{ ft}^2}{(260-202) \text{ mile}^2}$$

$$= \frac{590 \times 10^6 \text{ ft}^2}{58 \text{ mile}^2 \times (\frac{27.88 \times 10^6 \text{ ft}^2}{\text{mile}^2})}$$

$$\text{Vertical/horizontal growth ratio} = .365$$

Many of the above-mentioned indicators are only parts
of the overall Miami-Dade County system. Indicators of long-
range growth for the system are those which reflect the growth
of the system as a whole. Two of these parameters are devel-
oped land and population, both of which are plotted in Fig.
12 from approximately 1900 to 1972. The graph of developed
land was constructed by planimetering maps from the Dade
County Planning Department, Research Division, 1973. The
shape of the curve is suggestive of logistic growth. The
data which were used to construct these curves are presented
in Table 5, which also includes the rate (velocity) of devel-
opment computed by taking the total development over ten-year
increments and dividing by ten to get an average yearly rate
of development. Another indicator of long-range growth is
total fossil fuel energy consumed, a plot of which is pre-
sented in Fig. 5b from 1950-72. It should be possible to
determine various storages and flows in the system if the
total energy needed to support a given level of structure is
known. Figures 13 to 15 show effective buying income, retail
sales, total budget, number of telephones, number of tourists,
sales tax, and building structure as a function of the total
fossil fuel energy supporting the system and as a function
of the sum of electrical and gasoline energy consumption.
Several of these curves are almost straight-line growth
curves while others are close to piecewise linear; the slope
of the curve for sales tax in Fig. 15 seems to be increasing,

Table 5

Long-Range Urban Indicators

Year	Developed Land, Square Miles	Population, Millions	Population Density, People/Square Mile	Rate of Development, Square Miles/Year[a]	Fossil Fuel Energy Density, Kcal/meter2/day
1920	13	0.05	3846		
1930	34	0.125	3676	2.1	
1940	64	0.275	4297	3.0	
1950	109	0.495	4541	4.5	109
1960	202	0.94	4653	9.3	170
1970	247	1.27	5142	4.5	285
1972	260	1.37	5269	6.5	300

[a]Rate of development was calculated by taking the change in developed land over a ten-year period and dividing by ten to put it on a yearly basis.

Fig. 12.   Total population and developed land for Dade County from 1920-72.
Developed land in units of square miles; total population in millions.
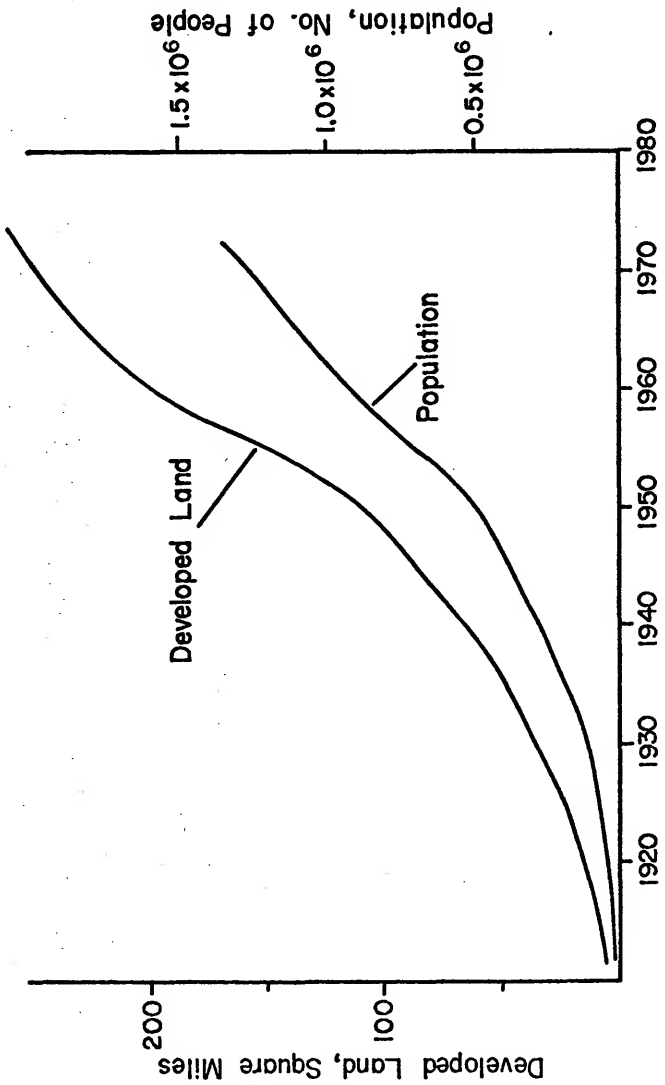
Fig. 13.   Several parameters in Dade County as a func-
           tion of total fossil fuel energy.

       a. Total budget, retail sales, and effective
           buying income as a function of total
           fossil fuel energy supporting the system
           of Dade County.

       b. Number of tourists, number of telephones,
           and sales tax collections as a function
           of total fossil fuel energy supporting
           the system of Dade County.

68

(a)

(b)
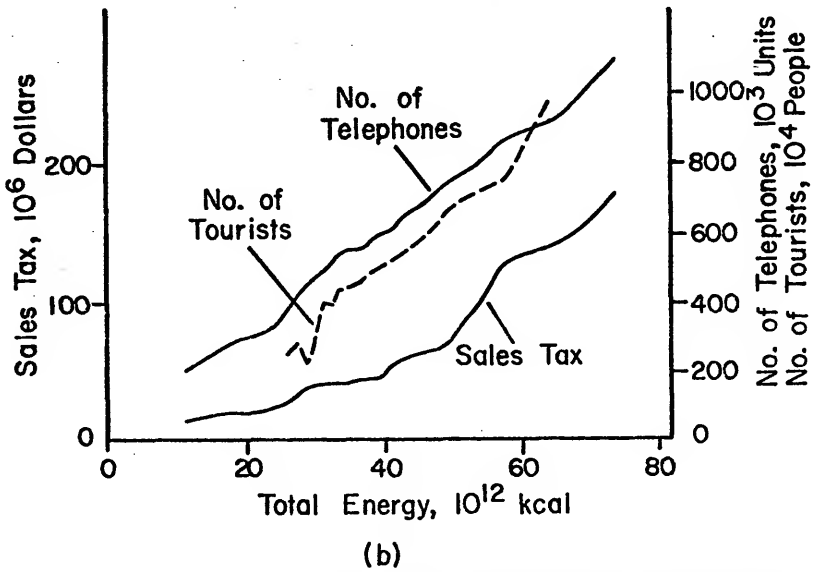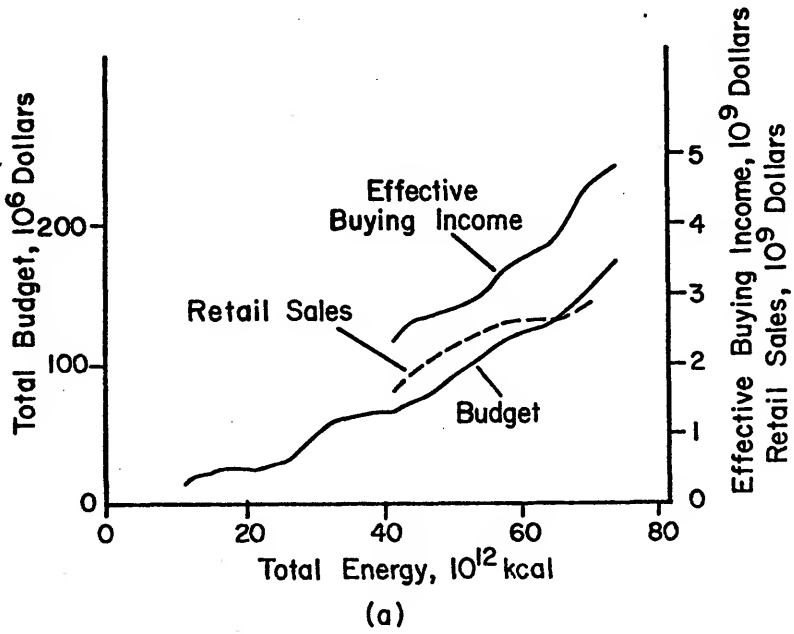
Fig. 14. Building structure and economic flows as func-
          tions of fossil fuel energies.

          a. Building structure as a function of total
              fossil fuel energy supporting the system
              of Dade County for two different rates of
              depreciation.

          b. Effective buying income, number of tourists,
              number of telephones, and retail sales as
              functions of electrical plus gasoline energy
              supporting the system of Dade County.
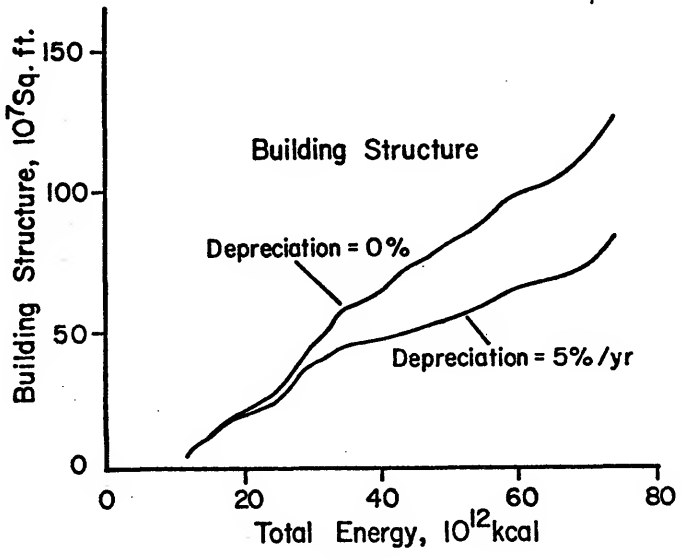
(a.)
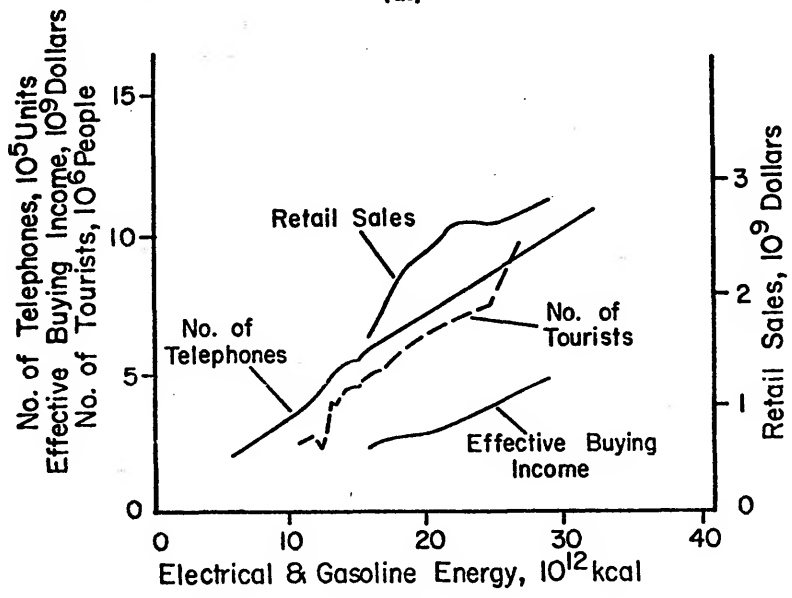
(b.)

Fig. 15. Effective buying income, sales tax collec-
          tions, and total budget as functions of
          electrical plus gasoline energy supporting
          the system of Dade County.

Fig. 16. Rate of change per year for total energy,
          electrical energy, and gasoline energy for
          yearly intervals from 1950-51 to 1971-72.
          All units in 10^{12} Kcal (FFWE).
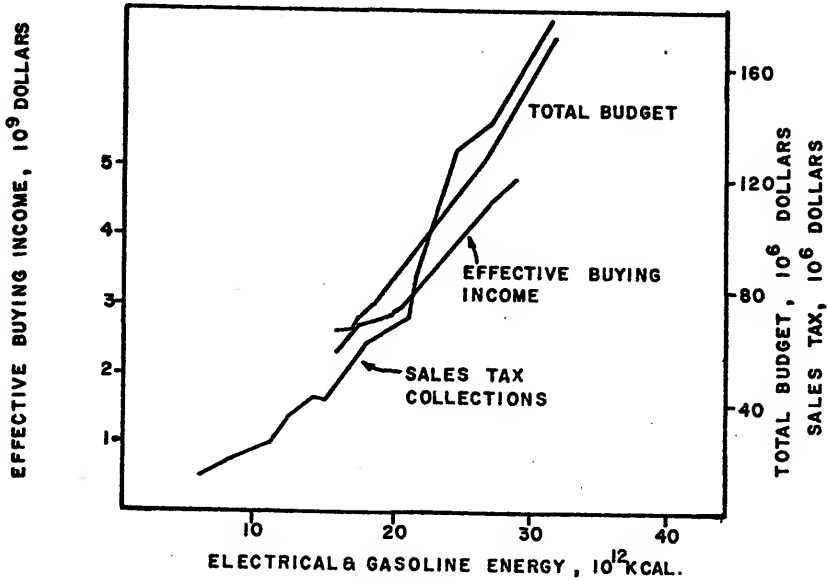
Fig. 15
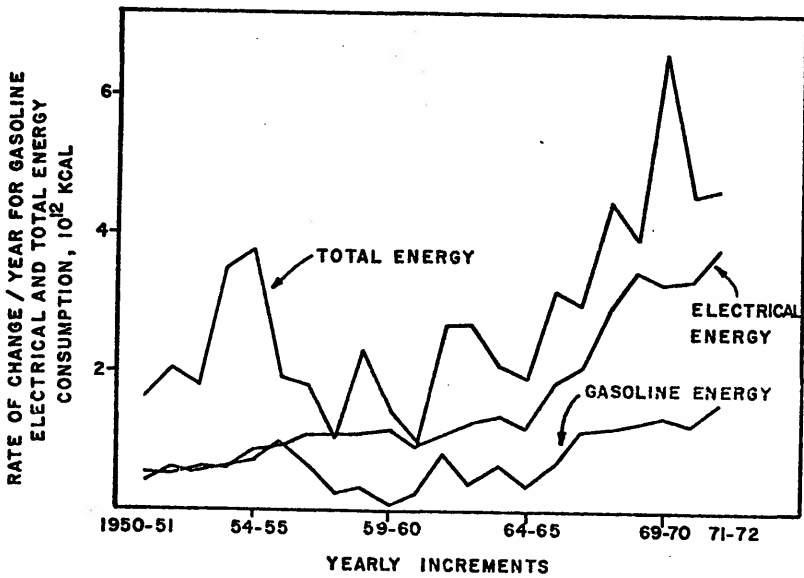
Fig. 16

Fig. 17.   Rates of change for economic flows and water
           consumption in Dade County.

           a.   Rate of change per year for effective
                buying income, retail sales and sales
                tax for yearly intervals from 1950-51
                to 1971-72.

           b.   Rate of change per year for total budget
                and water consumption for yearly inter-
                vals from 1950-51 to 1971-72.

(a)

(b)

Fig. 18.   Rates of change for labor force, population
           and number of telephones in Dade County.

       a.   Rate of change per year for labor force
            and population for yearly intervals
            from 1950-51 to 1971-72.

       b.   Rate of change per year for number of
            telephones for yearly intervals from
            1950-51 to 1971-72.

(a)

(b)
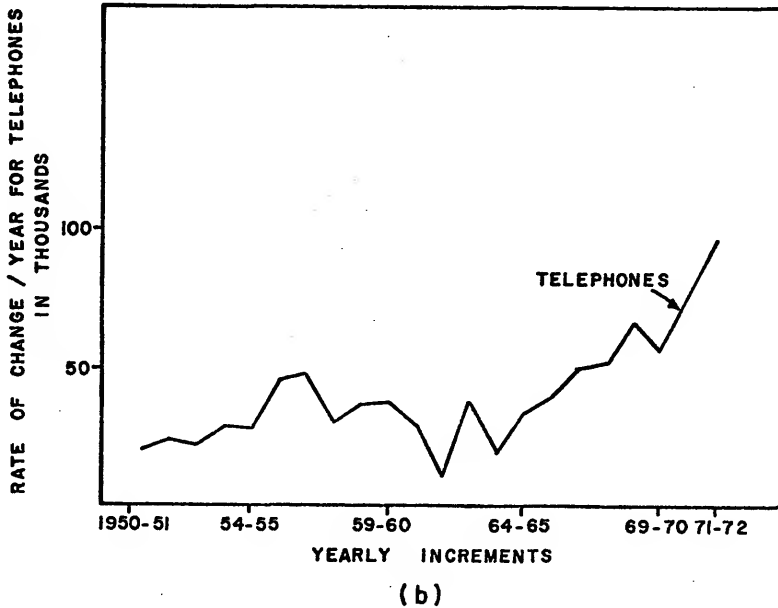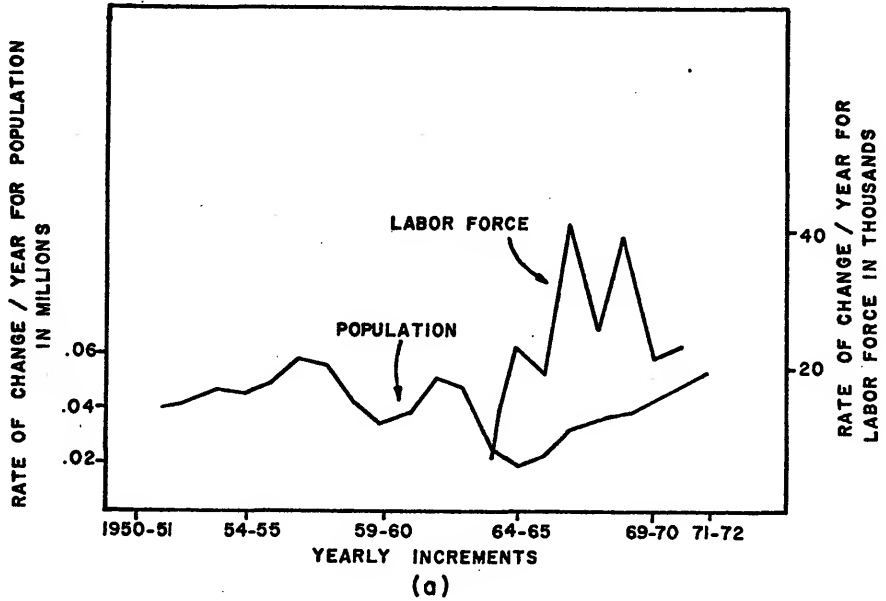
indicating a power function relation to the sum of electrical and gasoline energies in the system.

If the city indicators discussed above are plotted on a graph as a function of time (Figs. 5 to 11), then trends (rates of change) can be identified. This is further needed information when comparing different urban systems in addition to Table 4 of city indicators. The rate of change (velocity) of flows and storages in the system can be derived from the graphs over time. The rates of change of all the urban parameters are graphed in Figs. 16 to 18 from 1950-72. These graphs are further discussed and analyzed in the Data section.

General Overall Model of Miami-Dade County

This section presents an overall macro-model of the Miami-Dade system for purposes of describing system components, interactions, and numerical values of flows and storages. Figure 19 is the diagrammatic representation of the system with accompanying Table 6, which delineates numerical values and associated calculations and assumptions. The circled numbers of Fig. 19 refer to pathway numbers in Table 6. The outside forcing functions have been grouped into three main categories, namely, fossil-fuel energy and goods, natural energies, and money inputs. This grouping was chosen so that Fig. 19 represents a general urban model since all urban regions depend on these outside forcing functions to greater

Fig. 19. Overall detailed model of the Miami-Dade urban system showing values for flows and storages.
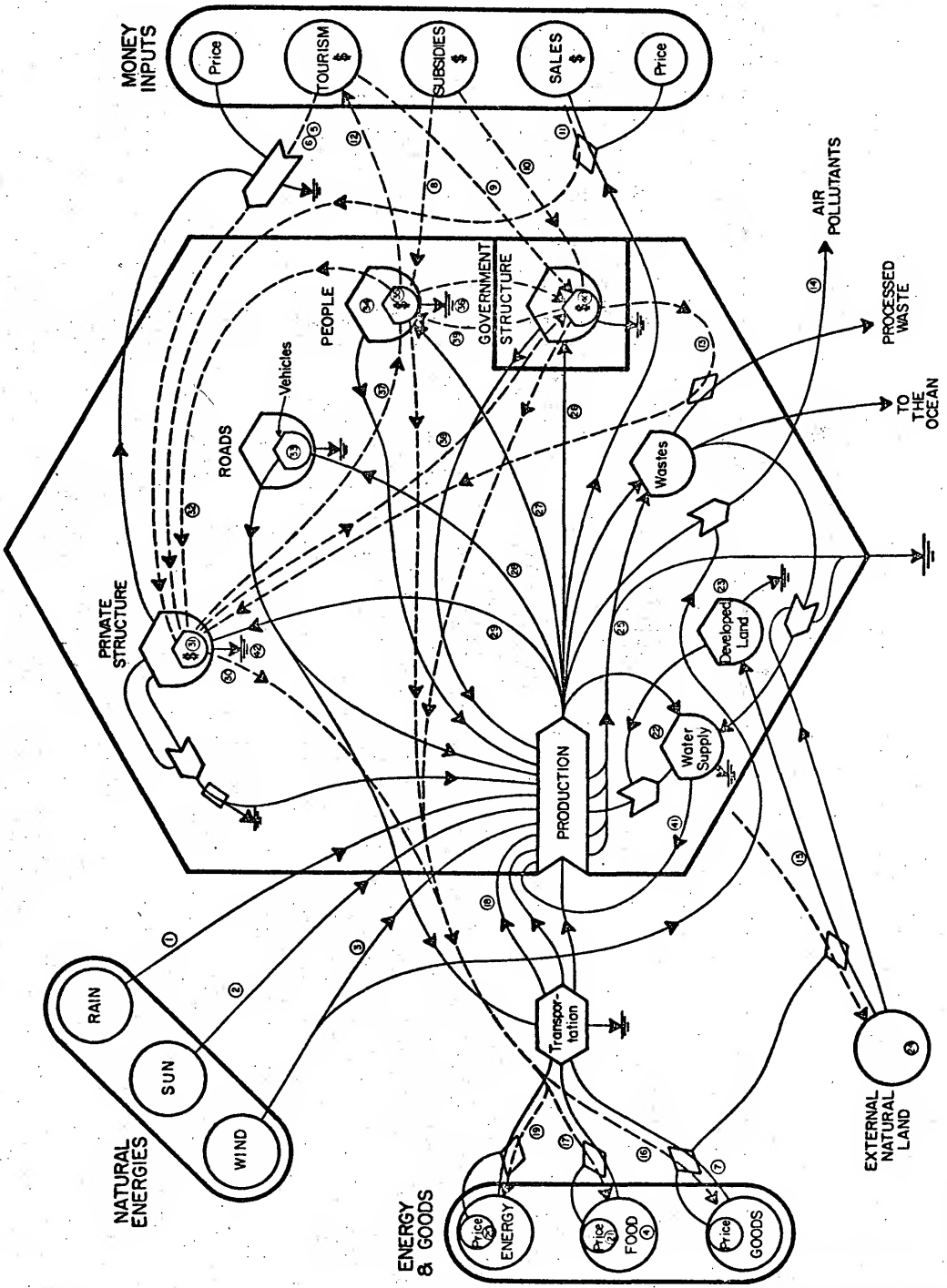
Table 6

Storages and Flows for Model in Figure 19

Pathway No. on Fig. 19a Note[b]	Description	Numerical Value	Reference[c]
1	Rainfall	222×10^{10} gal/yr	Windham
2	Sunlight	73.6×10^{14} Kcal/yr	How Dade Does It Right, MDPT, 1972; Mineral Industrial Surveys, 1950-72; Annual Report of Fla. Gas Transmission Co., 1971
3	Wind Energy Dissipated to Ground	$.38 \times 10^{12}$ Kcal	
4	Food Consumption	$.3 \times 10^{12}$ Kcal/yr	U.S. Census of Agriculture, 1972
5	Tourists	10^{7}/yr (1973)	Annual Financial Report of Metropolitan Dade County, MDCP, 1971
6	Tourist Dollar Flow	3×10^{9} dollars/yr	Ibid.; The Dade County Economy, MDCP, 1971
7	Imports of Motor Vehicles	29,000 vehicles/yr (1972-73)	Dade County Dept. of Transportation
8	Transfer Payments and Property Income	1.4×10^{9}	Dade County Economic Base Study, MDCP,1960; Fla. Statistical Abstract, 1973

Table 6 - Continued

Pathway No. on Fig. 19[a]	Note[b]	Description	Numerical Value	Reference[c]
9	7	Income to Gov't from Tourists	$7.86x10^6	Dade County Economic Base Study, MDCP, 1960; The Dade County Economy, MDCP, 1973; Conversation with Jay Yelton, State Economist
10		External Federal Subsidies	$856x10^6	Federal Information Exchange System County Summaries, 1970
12	8	Taxes	$1.36x10^9 (1972)	Dade County Economic Base Study, MDCP, 1960; Annual Financial Report, MDCP, 1971; Fla. Statistical Abstract, 1973; The Dade County Economy, MDCP, 1973
13		Expenditures for Air Pollution Control and Solid Waste Control	$.45x10^6 (1971-72)	Dade County Budget, Bd. of County Commissioners, 1971-72
14		Air Pollutants Generated	915,453 tons	
15		Rate of Land Development from Natural to Developed	4.8 sq. miles per year	Urban Environmental Changes, MDCP, 1972; Aerial photographs, 1973; see Table 10
16		Money Spent for Vehicles	$2.75x10^9 (1972)	Fla. Statistical Abstract, 1973
17		Money Paid for Food	$1.19x10^9 (1972)	Ibid.

Table 6 - Continued

Pathway No. on Fig. 19[a] Note[b]	Description	Numerical Value	Reference[c]
18	Total Fossil Fuel Energy Used in System	73.63×10^{12} Kcal/yr (1972)	Fla. Statistical Abstract, 1973; Dade County Economic Base Study, MDCP, 1960; Annual Financial Report, MDCP, 1971; The Dade County Economy, MDCP, 1973; Minerals Yearbook; Fla. Gas Transmission Co.'s Annual Report, 1971
19	Money Paid for Fuels	59.2×10^{7} (1972)	Ibid.
20	Price of Fossil Fuel Energy	$.8 \times 10^{-5}$/Kcal	Ibid.
21	Price of Food	$.834 \times 10^{-3}$/Kcal	Fla. Statistical Abstract, 1973
22	Water Supply	9×10^{12} gal	Windham
23	Developed Land Area	260 sq. miles	Aerial photography, Jan., 1973; see Table 10.
24	Land Area with Natural Self-maintaining Systems	1690 sq. miles	Ibid.
25	Solid Waste Generated	1600 lbs/person/yr Total=1.07×10^{6} tons	Ibid.

Table 6 - Continued

Pathway No. on Fig. 19[a]	Note[b]	Description	Numerical Value	Reference[c]
26	21	Rate of Building Growth in Public Sector	1.53×10^6 sq. ft (1972)	Annual Financial Report, MDCP, 1971; How Dade Does It Right, MDPT, 1972; Economic Survey, MDCP, 1970
27		Births and Net Migration	50800 (1972)	U.S. Census, 1970
28		No. of Vehicles Bought	26,987 vehicles for 1970	Dade County Dept. of Transportation; Fla. Statistical Abstract, 1973
29	22	Rate of Building Growth in Private Sector	1.53×10^8 sq. ft (1972)	Annual Financial Report, MDCP, 1971; How Dade Does It Right, MDPT, 1972; Economic Survey, MDCP, 1970
30	23	Total Structure of County Excluding Gov't Structure	1.09×10^9 sq. ft	Ibid.
31	24	Money Held by Business	$\$1.46 \times 10^9$	Fla. Statistical Abstract, 1973
32	25	Retail Sales	$\$2.5 \times 10^9$ (1972)	Dade County Economic Base Study, MDCP, 1960; Annual Financial Report, MDCP, 1971; Fla. Statistical Abstract, 1973; The Dade County Economy, MDCP, 1973
33		No. of Vehicles	850×10^3 (1971-72)	Dade County Dept. of Transportation

Table 6 - Continued

Pathway No. on Fig. 19a	Note[b]	Description	Numerical Value	Reference[c]
34		Total Population	1.37×10^6 people	U.S. Census, 1970; How Dade Does It Right, MDPT, 1972
35	26	Money Held by People	$\$1.46 \times 10^9$	Fla. Statistical Abstract, 1973
36		Deaths	14627 (1972)	U.S. Census, 1970
37	24	Private Income	$\$4.75 \times 10^9$ (1972)	Dade County Economic Base Study, MDCP, 1960; Annual Financial Report, MDCP, 1971; Fla. Statistical Abstract, 1973; The Dade County Economy, MDCP, 1973
38		Sales Tax	$\$178.6 \times 10^6$ (1972)	Ibid.
39	27	Government Structure	$\$1.09 \times 10^7$ sq. ft	Ibid.
40		Money Held by Government	$\$3.26 \times 10^8$	Fla. Statistical Abstract, 1973; Dade County Budget, Bd. of County Commissioners, 1971
41		Water Consumption	59.6×10^9 gal (1972)	How Dade Does It Right, MDPT, 1972
42		Depreciation	5%/yr	

[a]Pathways on Fig. 19 are circled.
[b]Notes are contained in Appendix II.
[c]MDCP stands for Metropolitan Dade County Planning Department; MDPT stands for Miami-metropolitan Department of Publicity and Tourism.

or lesser degree. For example, for an industrial city an industry storage and outflow of industrial goods in exchange for money would be substituted for tourism. As can be seen from the diagram, the major forcing functions for the Miami-Dade region include fossil fuel and food energies, tourist dollar flow, federal economic subsidies, sales of goods, population migration, natural energies, and external land available for development. The flow of tourists in and out of the region has been represented by the tourist money coming into the system which is inversely proportional to the price of goods and services in the external (U.S.) economy. In fact, all prices have been assumed to be determined by the economy of the United States as a whole, which reflects world-wide fuel availability and inflation.

The main storages which have been chosen to represent the system are private structure, roads and vehicles, population, government structure, water supply, developed land, wastes, and money. It can be seen that the production of structure and people is dependent on an interaction of all segments of the system, i.e., complex systems are highly integrated. This interaction depends on the natural energies of the system which are necessary for survival and provide work services for man. The wind energies of the system are especially important in maintaining the air quality of the system which serves as an attraction for people and tourists. Depreciation on all structures has been included to represent decay and is assumed to be 5%/year for a mean building life

of 20 years. The entire system is enclosed in the hexagonal symbol representing an autocatalytic system.

Another main aspect of the model are the pathways of money flows. These include the external sources and sinks of money along with the internal cycles of wages and sales which account for distribution within the system. It is seen that developed land is generated by available monies within the system for purchase of external land. In a sense the model is the superimposition of two models, one depicting the flow of energy, people and goods through the system while the other describes the money flows. These two systems are connected through price interaction equations (see Fig. 3 and later simulated models).

Urban Mini-Model Driven by External Storage of Fossil Fuels and Linear Price Functions

In Fig. 20 is a simple model which aggregates the structure of the city (meaning square feet of buildings) into one storage and the money available for spending into another storage. It is assumed that the growth of structure, represented by J_2, is a product function of the structure Q_1, the money storage, M, and the fossil fuel, F, which means that all three variables are necessary for growth to occur. If, for example, money flows out of the system M will decrease with a resulting decrease in the rate of growth, a consequence of limited capital. Compensating for the growth of structure is an assumed depreciation rate of 5% per year, represented by a

flow out of the storage, Q_1. Because of the simplicity of this model the money flows are broken into three main types. The inflow of money, K_1I_2, is that derived from tourism and transfer payments; the outflow, J_1P_1, is the money spent for energy; the remaining outflow, K_5MP_1, is money spent for goods and services and can be looked upon as the money neces- sary to keep the economic system functioning including inter- change between people. This model could be used for any urban system provided the flows are known or approximated.

Since this model considers the energy source as a stor- age, the response of the model will vary depending on the amount of fuel assumed available. For this simulation the total proven fossil fuel reserves have been used (Auer, 1974) with a 40% recovery rate (Ballentine, 1974). Other available energy sources will be considered in later models. Monies spent for fuels and goods and services are a function of the price, P_1, so that the response of the model becomes depen- dent on the price function. This price is assumed to be determined external to the system, generated by the inter- actions of the U.S. and world economies.

Since there is so much uncertainty in the nature of future prices, several price functions are used in order to generate families of curves. The inflow of money, K_1I_2, is assumed to increase at a rate of $.012 billion/yr, which is the average rate of increase from 1950-72. This is probably unrealistic but is an optimistic assumption in terms of a supply of money to the system. Four cases of a price function

are used, namely, P_c = constant price, $.1P_c$ increase per year after 1973, $.2P_c$ increase per year, and $.5P_c$ increase per year after 1973. P_c was the existing price of fuel from 1952 to 1973. It is assumed that fuel prices are constant before 1973, an assumption which agrees well with the facts (Minerals Yearbook). Prices for goods and services are assumed to be some constant multiple of fuel prices.

Simulation output results are presented in Figs. 21 to 23. Figures 21 and 22a show the overall response of the three state variables and the money flow for fuels, J_1P_1, for four different price functions. The effect of different rates of increasing prices is clearly illustrated in Figs. 22b and 23 where families of curves are plotted for Q_1, M, F and J_1P_1. In Fig. 22b it is seen that for dP/dt > 0 (inflation rate greater than 0), structure peaks earlier and at a lower level than for dP/dt = 0 where dP/dt is the rate of price increase. The percentage difference in maximum structure between dP/dt = 0 and dP/dt = .5 P_c/yr is approximately (.65-.4)/.65 or 38.5%, separated in time by eight years, the result of greater outlays of money for fuels, goods, and services. Figure 23a shows the response of the money tank. It is seen that for P_1 = constant the money available continues to grow because of the assumed continuing input from outside the system. Each of the cases for dP/dt $\neq$ 0 gives an eventual steady-state value with the dP/dt = .5 P_c/yr condition 33% less than the dP/dt = .1 P_c/yr condition in 1990. The fuel curves shown in Fig. 23b are extremely interesting and show, in

Fig. 20. Simplified urban model of Miami-Dade County driven by outside storage of fossil fuels, external income, and linear price functions. The equations used to simulate the model were as follows:

$$\dot{F}_1 = -K_0 F Q_1 M$$

$$\dot{Q}_1 = K_2 F Q_1 M - K_4 Q_1$$

$$\dot{M} = K_1 I_2 - K_0 F Q_1 M P_1 - K_5 M P_1$$

$$\dot{P}_1 = 0 \text{ before } 1973$$

$$\dot{P}_1 = \text{constant after } 1973$$

Natural Energies

I_2 — External Income

$k_1 I_2$

Payment for

$ Goods & Services

Money

$k_5 MP_1$

M

Structure

Q_1

$J_2 = k_2 FQ_1 M$

$k_4 Q_1$

$J_1 P_1$

P_1

$J_1 = k_0 FQ_1 M$

F — Fossil Fuels

P_1 — Price
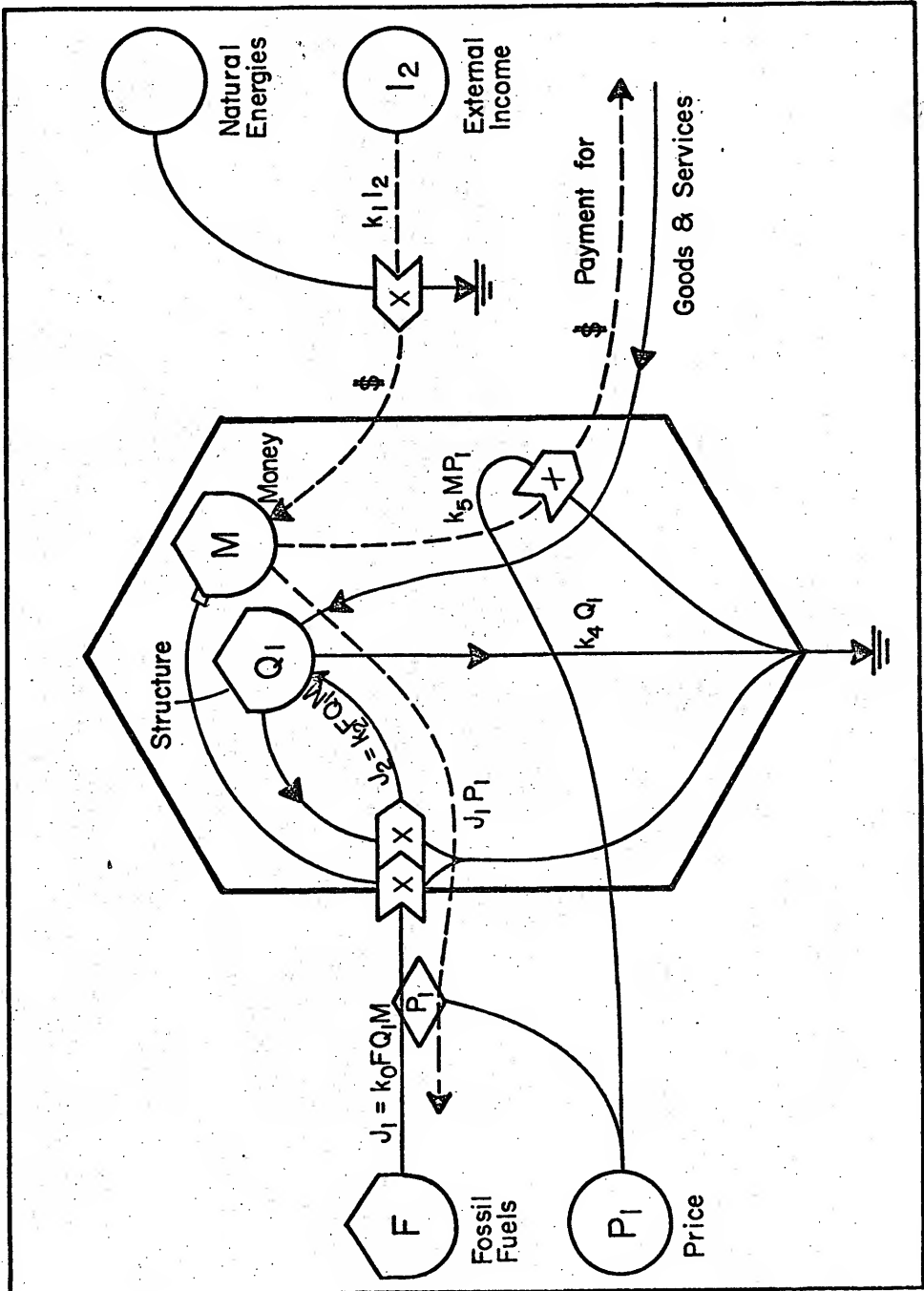
Table 7

Flows and Storages for Model in Figure 20

Mathematical Quantity	Note[a]	Description	Numerical Value	Reference
F	1	United States' Fossil Fuel Supply Available for Residents of Dade County	3.08×10^{15} Kcal	Auer, 1974
Q_1	2	Building Structure in Square Feet	app. 850×10^6 ft^2 (1972)	See Data section and Table 20
M	3	Monies Available for Purchasing	$\$2.737 \times 10^9$	"
$J_1 = K_0 F Q_1 M$	4	Fuel Consumption in Dade County	73.63×10^{12} Kcal (1972)	"
$J_2 = K_2 F Q_1 M$	5	Building Growth Rate	55×10^6 ft^2/yr	"
$K_1 I_2$	6	Income from Tourism and Transfer Payments	$\$4.0 \times 10^9$/yr (1970)	"
$J_1 P_1$	7	Money Paid for Fuels	$\$59.2 \times 10^7$	"
$K_4 Q_1$	8	Depreciation of Structure	5%/yr	"
$K_5 M P_1$	9	Money Paid for Goods & Services	$\$3.4 \times 10^9$/yr	"
P_1	10	Price for Fuels	$\$0.804 \times 10^{-5}$/Kcal	"

[a]Notes are contained in Appendix II.

Fig. 21. Simulation results for model in Fig. 20.

   a. Simulation results for model in Fig. 20
       with price constant. Numbers on vertical
       axis indicate units that variables are
       expressed in.

   b. Simulation results for model in Fig. 20
       with price increasing 10% per year after
       1973. Numbers on vertical axis indicate
       units that variables are expressed in.
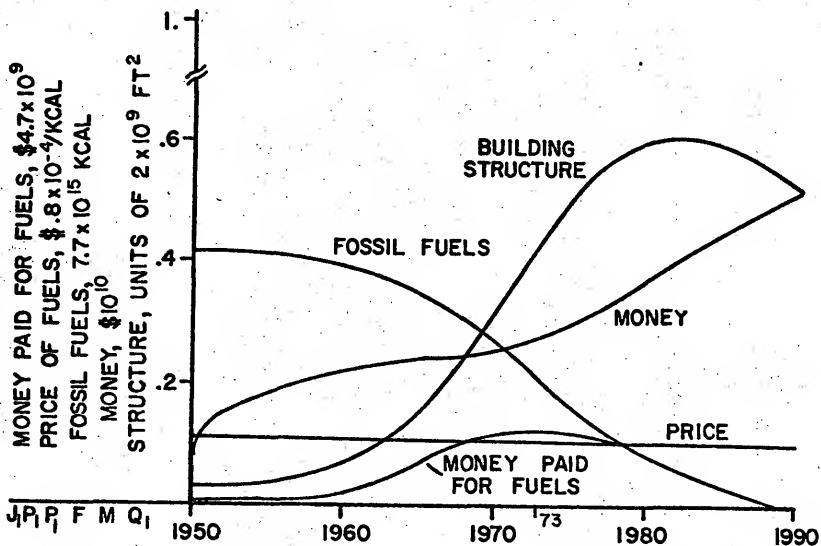
(a.)
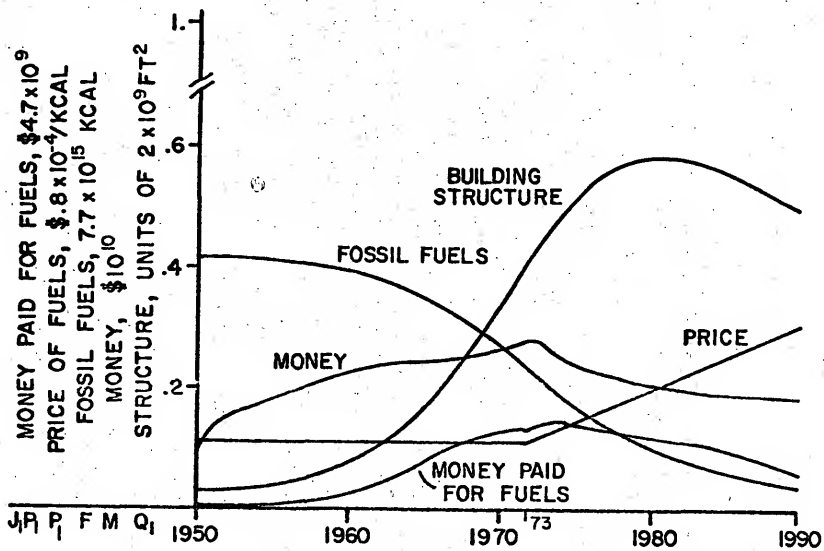
(b.)

Fig. 22. Simulation results for model in Fig. 20.

      a. Simulation results for model in Fig. 20 with price increasing 20% per year. Numbers on vertical axis are units that variables are expressed in.

      b. Simulation results for model in Fig. 20 showing a family of curves for building structure as a function of four different inflation rates. Inflation rate is the percentage increase of 1973 price occurring each year.
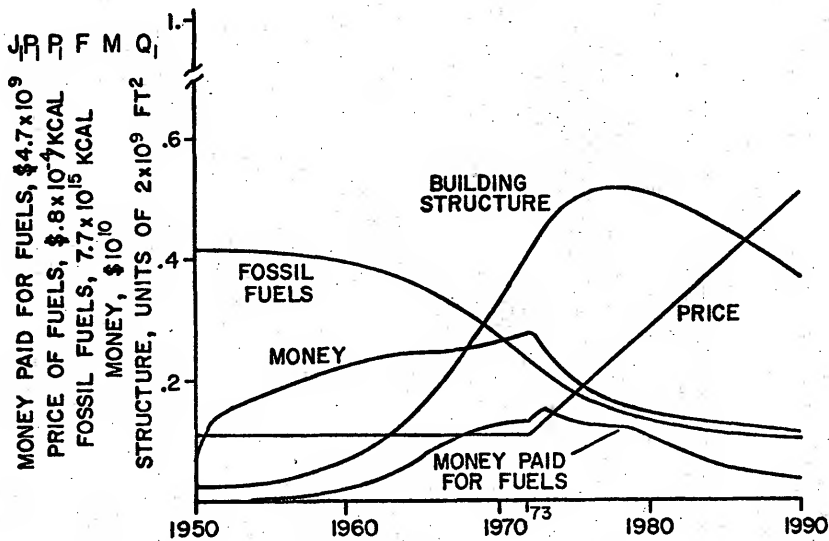
(a)
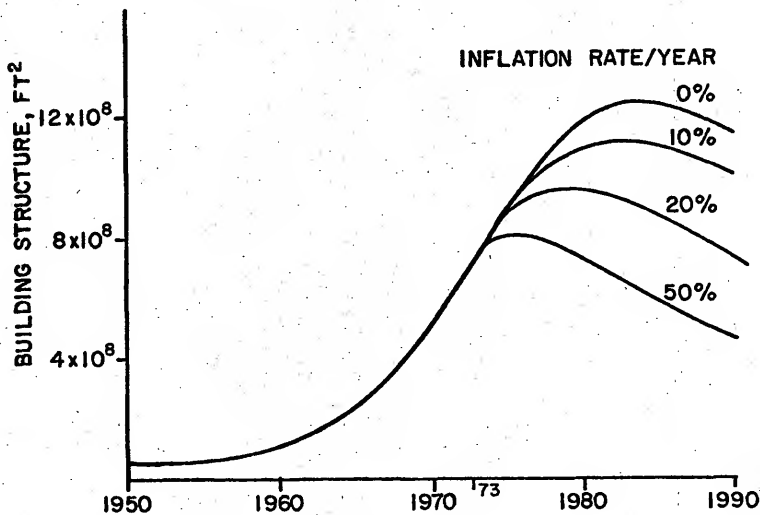
(b)

Fig. 23. Simulation results for the model in Fig. 20.

      a. Simulation results for model in Fig. 20
          showing a family of curves for money
          supply for four different rates of infla-
          tion. Inflation rate is the percentage
          increase of 1973 price occurring each
          year.

      b. Simulation results for model in Fig. 20
          showing a family of curves for fossil-
          fuel supply for four different inflation
          rates.

      c. Simulation results for model in Fig. 20
          showing a family of curves for money paid
          for fuels for four different inflation
          rates.

(a.)

(b.)

(c.)
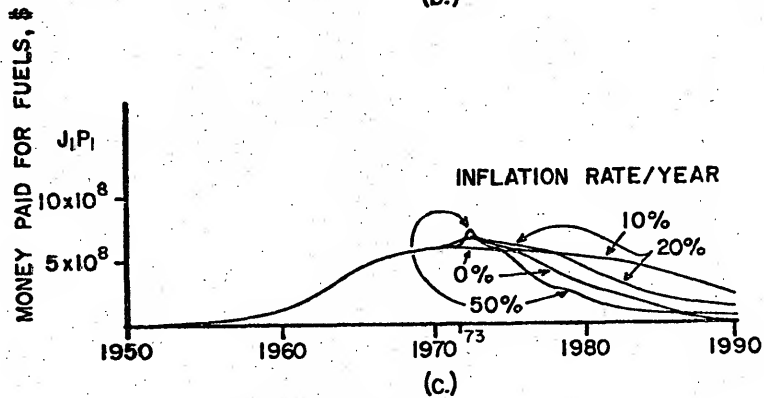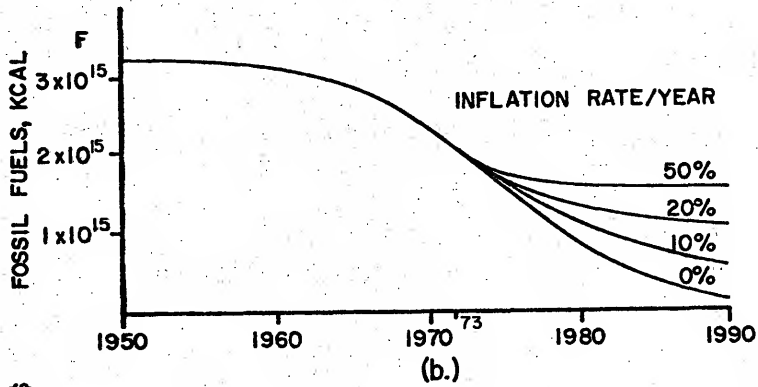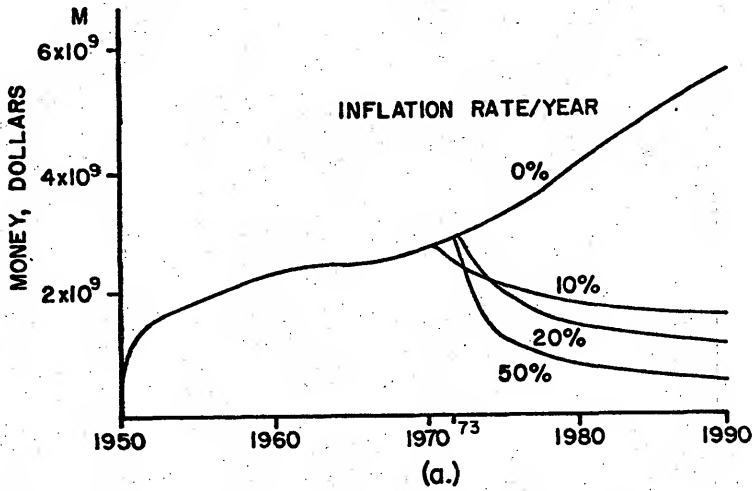
effect, the results of supply and demand. It is seen that higher price levels lead to smaller consumption of fuels and an eventual higher level of fuel remaining. In fact, in 1990 there is 10 times as much fuel remaining for $dP/dt = .5\ P_c/yr$ than for $dP/dt = .1\ P_c/yr$. Finally, in Fig. 23c is shown the different outlays of money for fuels and it is seen that higher prices lead to a higher pulse in fuel purchases followed by a lower level of monies spent for fuels, probably because of a lower level in money supply, M. As can be seen from Fig. 23a the $.1\ P_c/yr$ price function triggered slightly earlier than 1973, which would introduce some small error into the 10% curve in Fig. 23c for fuel expenditures.

What the results of this and other models in this dissertation mean for life in the city is discussed later on in the Discussion section. How will fewer cars, buildings, and little or no net growth affect the life-style of the inhabitants?

Urban Mini-Model Driven by External Linear Functions for Energy and Price

In Fig. 24 is a model similar to the model in Fig. 20 except that, instead of a storage of fossil fuel as an energy source, an arbitrary function may be programmed to drive the model. All the money flows are the same functionally as in the previous model. Maintenance energies are assumed to be a square drain on structure because of the increased interaction between parts as the system gets larger (Lamm, 1973). The model diagram and associated equations are shown in Fig. 24. For numerical values of the flows see Table 7.

As in the previous model the price function, P_1, is variable but so also is the energy function, E. Again, it is difficult to assess how P_1 and E will change in the future, especially since they are probably coupled in some way, so several cases are considered. If there are more fossil fuel reserves than is generally assumed and nuclear power is a net-yielder of energy, then the available energy can continue to grow. In order to simplify the simulations, linear functions were used for E as well as P_1. The first case considered is a linear increase of E from 1950 to 2000 with the values at 1950 and 1973 corresponding to actual energy usage. This corresponds to an increase of approximately $.24 E_0/yr$ where E_0 is the energy consumption for 1950 (approximately 11.24×10^{12} Kcal). A less optimistic energy outlook is portrayed by the same linear increase from 1950-73 followed by a leveling at the 1973 value. In order to maintain this level of energy consumption a net-yielding nuclear technology will have to be developed. As a last case, it is assumed that energy consumption peaks in 1973 and decreases linearly to the 1950 level by the year 2000. The price function was 20% of the 1973 level per year after 1973, i.e., $dP/dt = .2 \, P_c/yr$. Figure 25 depicts the overall behavior of the model for an assumed price function which increases at the rate of $dP/dt = .2 \, P_c/yr$ for the three different available energy functions discussed above. It is seen that even for steadily increasing energy the structure, Q_1, levels while the money supply decreases as monies spent for fuels increase almost in a

Fig. 24. Simplified urban model of Miami-Dade County with inflows of fossil fuel energy and external income with linear external price function. The equations describing the simulation model are:

$$\dot{Q}_1 = K_1 E Q_1 M - K_4 Q_1^2$$

$$\dot{M} = K_3 I_2 - K_2 E Q_1 MP - K_5 MP_1$$

$$\dot{P}_1 = 0 \text{ before 1973}$$

$$\dot{P}_1 = \text{constant after 1973}$$
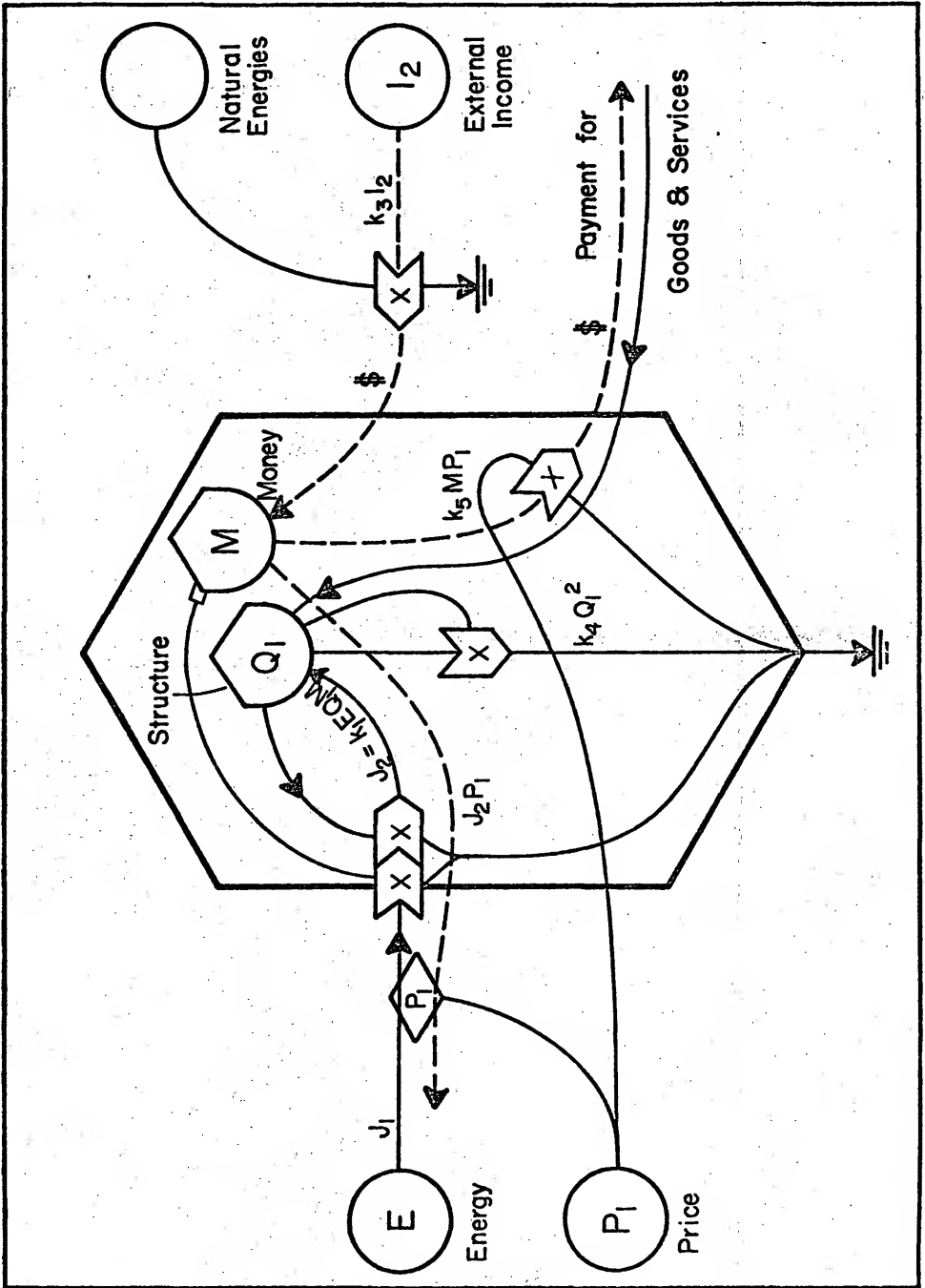
Fig. 25.   Simulation results for model in Fig. 24.

   a.   Simulation results for model in Fig. 24
        with energy increasing from 1950 to 2000
        at the rate of 2.7×10^{12} Kcal/yr. Numbers
        on vertical axis are in units that vari-
        ables are expressed in.

   b.   Simulation results for model in Fig. 24
        with energy increasing from 1950 to 1973
        at the rate of 2.7×10^{12} Kcal/yr and level
        from 1973 to 2000.

   c.   Simulation results for model in Fig. 24
        with energy increasing from 1950 to 1973
        at the rate of 2.7×10^{12} Kcal/yr and then
        decreasing at this rate from 1973 to 2000.

(a.)

(b.)

(c.)
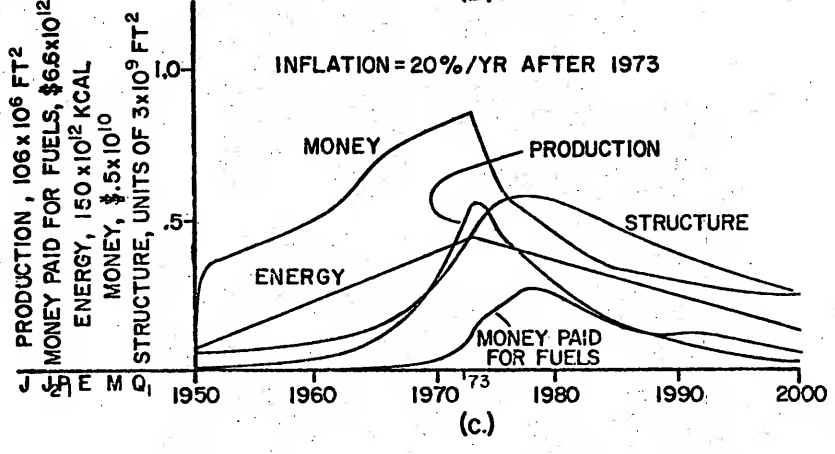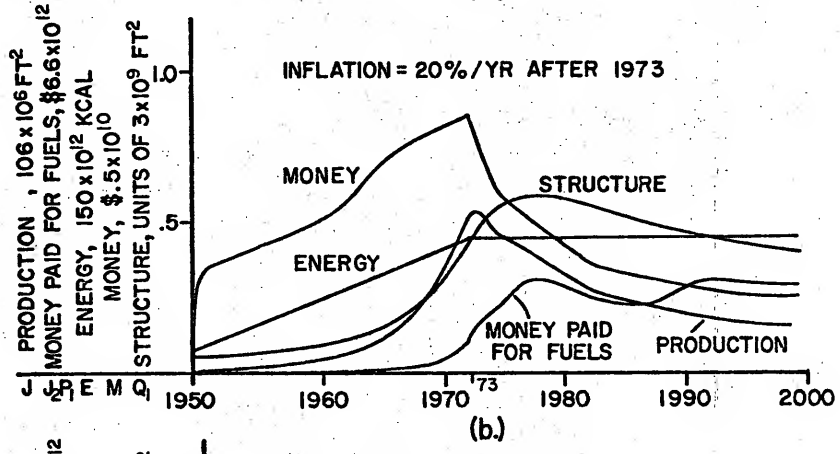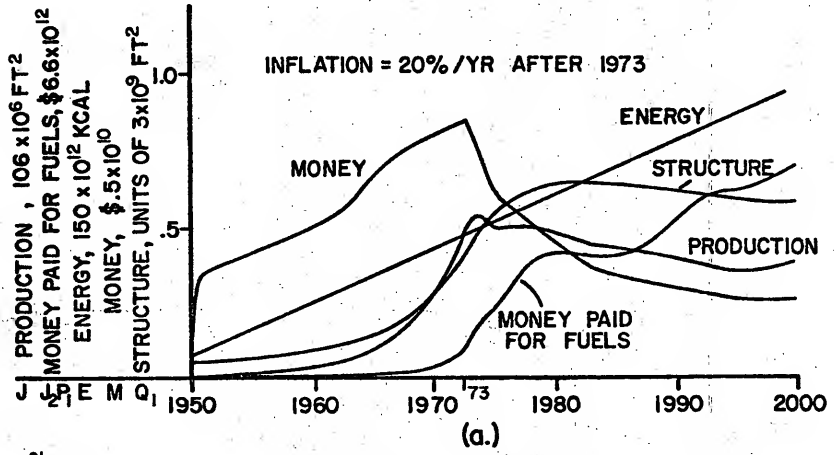
Fig. 26. Simulation results for model in Fig. 24.

     a. Simulation results for model in Fig. 24
        showing a family of curves for building
        structure as a function of three differ-
        ent energy functions.

     b. Simulation results for model in Fig. 24
        showing a family of curves for growth
        rate as a function of three different
        energy functions.
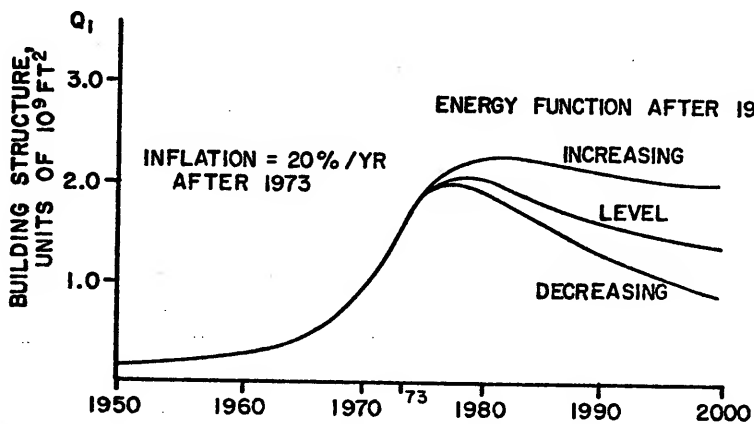
(a)
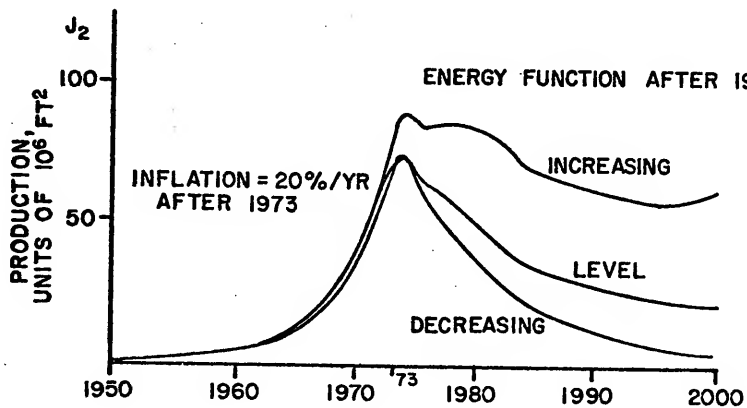
(b)

step-wise manner. The next two cases of energy leveling and declining result in lower levels of each parameter. It is interesting that in each figure, production, J_2, peaks in 1973 and declines thereafter while the peak in structure occurs about 3 to 6 years later, depending on the energy function. Figures 26a and 26b allow better comparison of the structure, Q_1, and production, J_2, for the three different energy functions. It is seen that increasing energy results in structure being approximately 45% higher. The energy added from 1973-2000 is given by

$$\int_{23}^{50} (6.8+2.9t) \times 10^{12} \ dt = 3040 \times 10^{12} \ Kcal$$

while for energy level from 1973-2000 the energy added is 1990 $\times 10^{12}$ Kcal. While the structure is 45% higher the energy maintenance of the city is approximately 53% higher. The production rate of the city, J_2, is much lower in the year 2000, being about 36% of the value for the energy increasing case. What alternative growth futures will mean for urban life is considered in the Discussion section.

Tourist Mini-Model for Miami-Dade County

In Fig. 27 is a model similar to those already presented but simulated in greater detail and containing features appropriate for Dade County. The money flows were separated into four major flows. The flow of tourist dollars was assumed to be directly dependent on available fossil fuels, structure

in the county, and natural energies in the system. It was
reasoned that as fossil fuels decline so will tourist travel.
Low levels of natural energies or man-made structure to pro-
vide services would also limit tourist allocation. Finally,
it was assumed that tourist flow was inversely proportional
to the price of travel where the price of travel was thought
to be closely related to the price of fuels. It was reasoned
that even if the cost of travel became very high there would
still be some tourism. This tourist flow could have been
programmed with a $(1-P_2)$ term but this would go to zero at
some critical price. Thus, the inverse function was used.
The flow of taxes out of the system was assumed proportional
to the money storage while the inflow of transfer payments
and government subsidies was assumed proportional to the popu-
lation. The flow of money through the price transactor, with
price P_1, was the difference between money to purchase food,
fuels and goods minus profits from manufacturing and property
income.

Two storages were included in this model which were not
present in previous models, namely, natural energies and popu-
lation. A stress on natural energies was assumed to be pro-
portional to developed structure. The flow of population
into the population storage was assumed to be dependent on
fossil fuels, money supply, and structure, all of which con-
tribute to the increase in population. This increase in popu-
lation consisted of natural increase plus migration. Most of
the recent population increase can be accounted for by

migration (see Fig. 6). As in previous models, the production of structure is also assumed to be dependent on these variables. Also included in this model were two price functions; P_2 is representative of the price of travel and P_1 is some mixed price for goods and fuels. Of course, P_1 is related to P_2 since they are both dependent on energy sources.

It was desired to find the response of the model to a step increase in the price of travel. To account for this the model was programmed with a step input for the price of travel, P_2, and a linearly increasing function for P_1. It was assumed that P_1 was increasing 20% of the 1973 level each year as in previous simulations. In summary, then, the rationale for using two different price functions was that the price of travel was closely associated with fuel prices and so this flow was programmed with a step input for P_2. The general price for goods, services, and fuels which connects the urban system to the outside economy was assumed to have a more gradual increase so that a linearly increasing function was programmed for P_1. Both of these price functions are assumed to be created external to the system.

The results of the simulations are presented in Figs. 28 to 30. Figures 28 and 29 show results for building structure, natural energies, population, tourist dollars and money supply. The curves generated for prices constant assume that prices remain constant until 1990. For the price increasing curves the price functions shown in Fig. 29c were used where the rate of increase of P_1 was 20% per year and P_2 was a step

Fig. 27. Tourist model for Miami-Dade County with major money flows. The equations used to simulate the model were as follows:

$$\dot{Q}_1 = K_6 FMQ_1 - K_7 Q_1$$

$$\dot{Q}_2 = K_8 Q_2 J_R - K_9 Q_1 - K_{10} Q_2$$

$$\dot{Q}_3 = K_{12} FMQ_1 - K_{13} Q_3$$

$$\dot{M} = K_1 \frac{Q_1 Q_2 F}{P_2} + K_{11} Q_3 - K_4 MQ_1 FP_1 - K_5 M$$

$$\dot{F} = -K_4' FMQ_1$$

$$J_R = J_0 K_0 J_R Q_2$$

$$\dot{P}_1 = 0 \text{ before } 1973$$

$$\dot{P}_1 = \text{constant after } 1973$$

P_2 is a step function with step increase at 1973

NATURAL ENERGIES

TRANSFER PAYMENTS

& FEDERAL SUBSIDIES

TAXES

J_0

J_R

$k_0 J_R Q_2$

$k_5 M$

$k_8 J_R Q_2$

NATURAL ENERGIES

Q_2

$k_{10} Q_2$

$k_1 \dfrac{Q_1 Q_2 F}{P_2}$

MONEY

M

STRUCTURE

$k_{11} Q_3$

POPULATION

Q_3

$k_{12} FMQ_1$

Q_1

$k_7 Q_1$

$k_{13} Q_3$

$k_9 Q_1$

$k_6 FMQ_1$

PRICE OF TRAVEL

P_2

TOURISM

FOSSIL FUELS

$k_4 MQ_1 FP_1$

$k_4' FMQ_1$

F

PRICE OF GOODS & FUELS

P_1
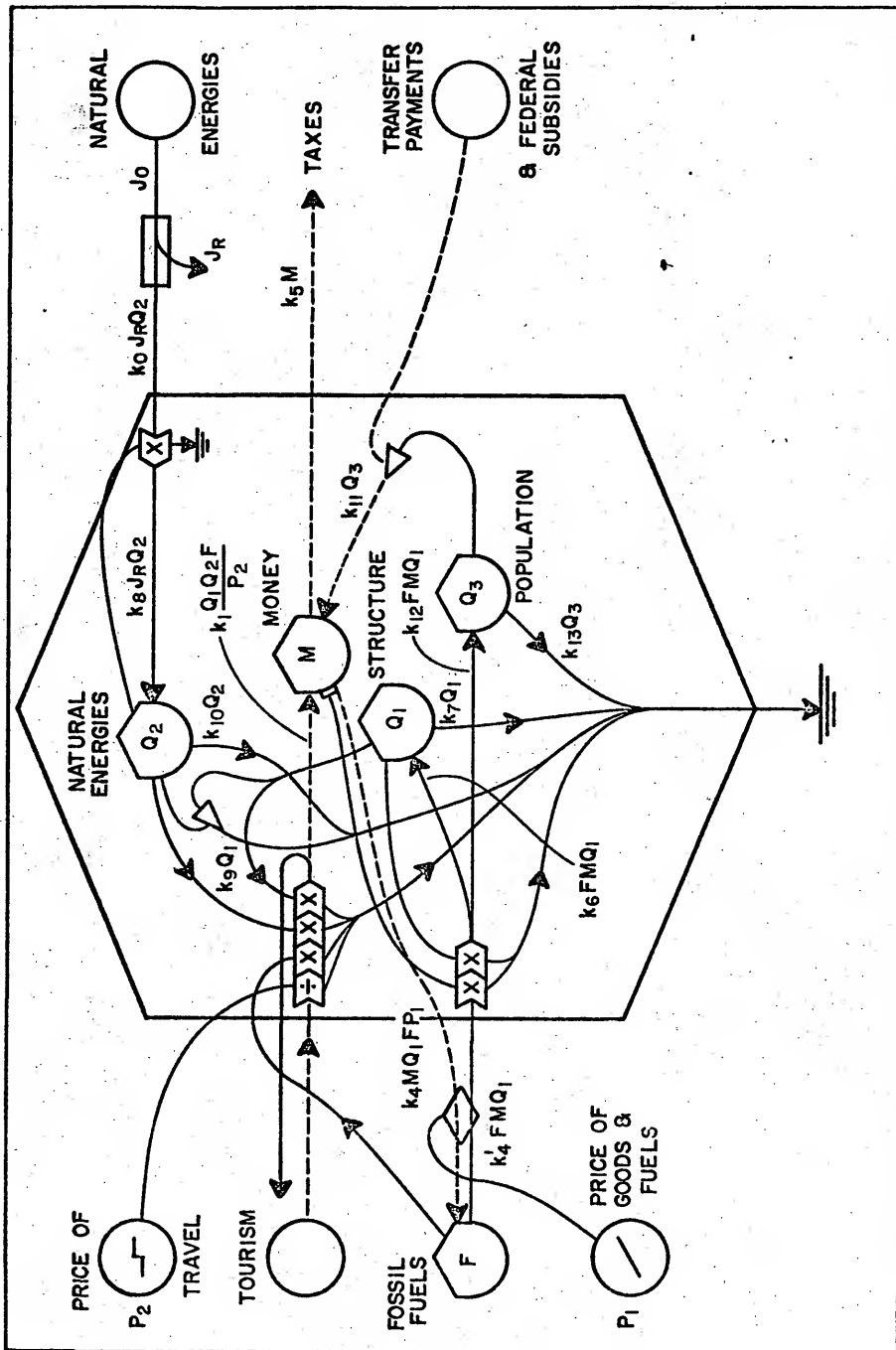
Table 8

Storages and Flows for Tourist Model in Figure 27

Mathematical Quantity	Note	Description	Numerical Value[a]	Reference
F	1	United States Fossil Fuel Supply Available to Residents of Dade County	3.08×10^{15} Kcal	Auer, 1974
Q_1	2	Building Structure in Square Feet	850×10^6 ft^2 (1972)	See Data section and Table 20
Q_2	3	Natural Energies	13.9×10^{12} Kcal (1972)	"
Q_3	4	Population	1.37×10^6 (1972)	"
M	5	Money Available for Purchasing	$\$2.74 \times 10^9$ (1972)	"
$K_4'FMQ_1$	6	Fuel Consumption in Dade County	73.63×10^{12} Kcal (1972)	"
$K_6 FMQ_1$	7	Building Growth Rate	55×10^6 ft^2/yr	"
$K_{12} FMQ_1$		Population Growth	50800/yr (1972)	"
$K_{13} Q_3$		Death Rate	14627/yr (1972)	"
$K_4 MQ_1 FP_1$	8	Money for Food, Fuels and Goods minus Manufacturing and Property Income	$\$2.65 \times 10^9$ (1972)	"
$K_7 Q_1$	9	Depreciation of Structure	5%/yr	"

Table 8 - Continued

Mathematical Quantity	Note	Description	Numerical Value[a]	Reference
$K_1 \dfrac{Q_1 Q_2 F}{P_2}$	10	Tourist Money Flow	3.2×10^9 (1972)	"
$K_5 M$	11	Outflow of Tax Money	1.36×10^9 (1972)	"
$K_{11} Q_3$	12	Transfer Payments plus Federal Subsidies	1.48×10^9 (1972)	"
$K_8 J_R Q_2$	13	Natural System Production	13.9×10^{12} Kcal	"
$K_{10} Q_2$	14	Natural System Decay	13.9×10^{12} Kcal	"
$K_9 Q_1$	15	Stress on Natural Systems	$.05 \times 10^{12}$ Kcal/yr	"

[a] All Kcal values are in Fossil Fuel Work Equivalents (FFWE).

NOTE: Notes are contained in Appendix II.

Fig. 28.   Simulation results for tourist model in Fig. 27.

a.   Building structure for two different price
     situations. One result is for prices
     constant; the other result is for the
     programmed price functions shown in
     Fig. 29c.

b.   Natural system energies for two different
     price situations.

c.   Total population for two different price
     situations.

(a.)

(b.)

(c.)
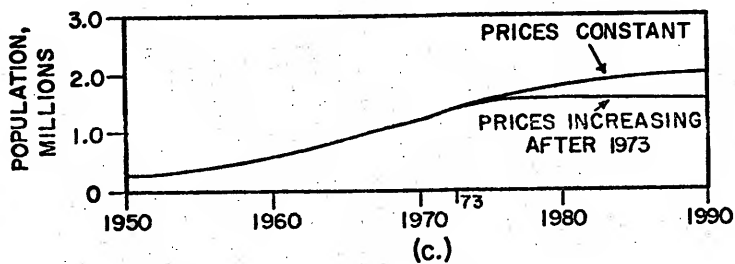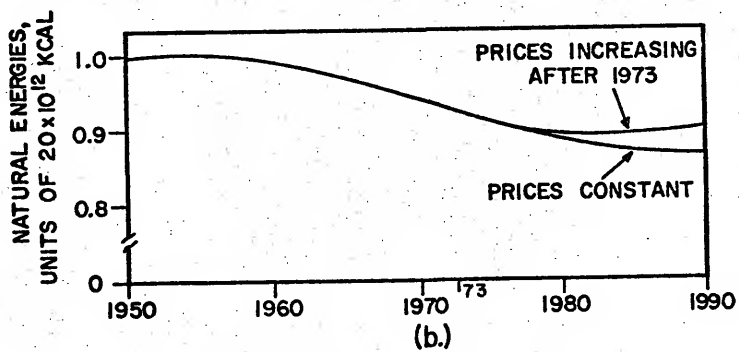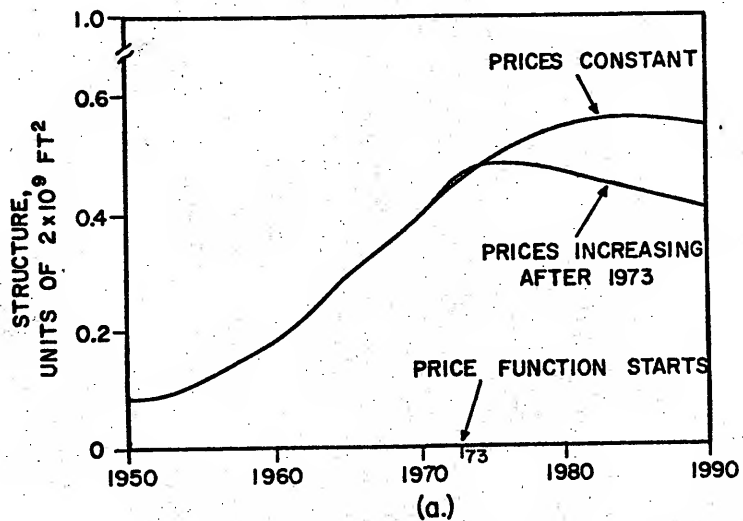
Fig. 29. Simulation results for tourist model in Fig. 27.

      a. Tourist dollar flow for two different price
         situations. One result is for prices
         assumed constant; the other result is for
         the programmed price functions shown in
         Fig. 29c.

      b. Money supply for two different price situa-
         tions.

      c. General form of the price functions pro-
         grammed for simulations. P_1 represented
         some mixed price for goods and fuels for
         the urban system, whereas P_2 represented
         a price more directly related to tourist
         travel.
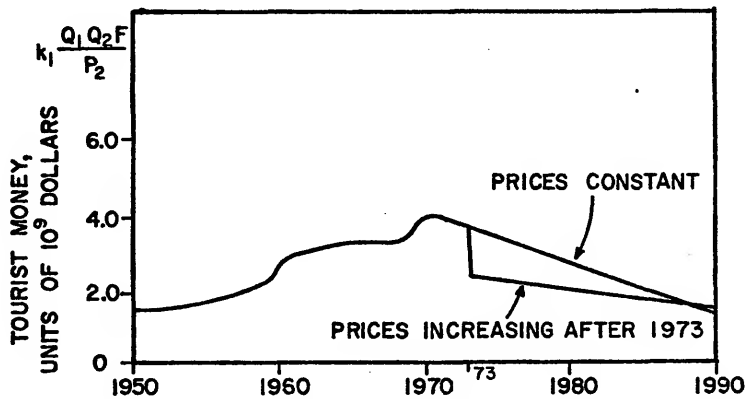
(a.)
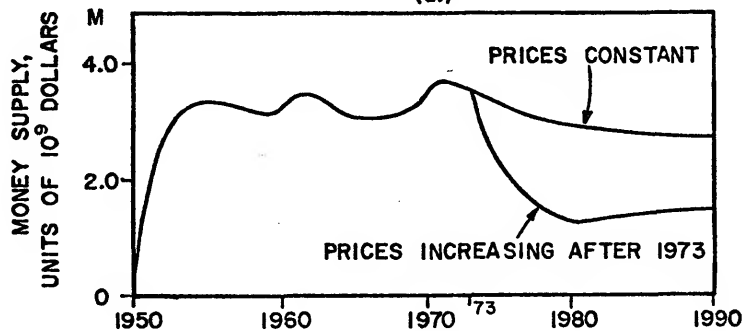
(b.)
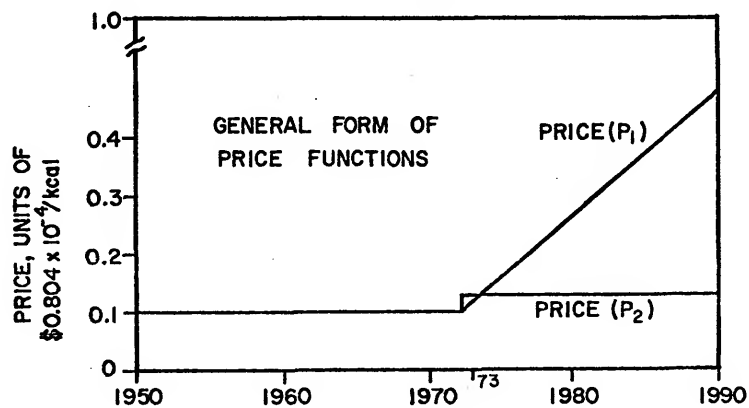
(c.)

Fig. 30. Simulation results for tourist model in Fig. 27
         with fossil-fuel storage double that used for
         simulation results shown in Figs. 28 and 29.

     a. Building structure for two different rates
         of inflation after 1973. The rate of
         increase of price refers to the slope of
         the P_1 price function after 1973 as shown
         in Fig. 29c. The P_2 price function is
         assumed to remain the same.

     b. Total population for two different rates
         of inflation after 1973.

(a.)

(b.)
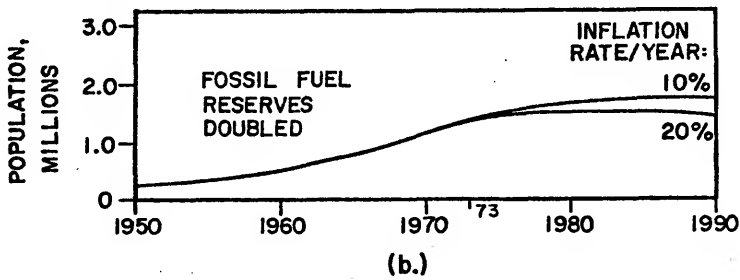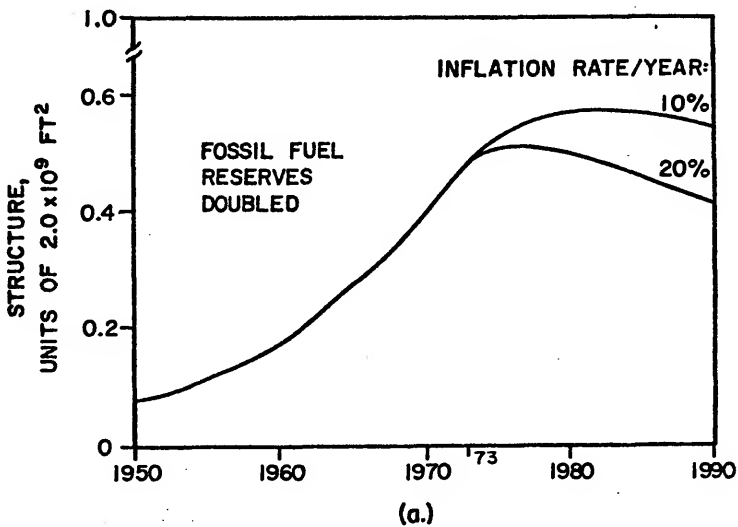
function. It can be seen from the curves that increasing
prices inhibit the growth of structure, population, tourism,
and money supply whereas the natural system energies recover
and end up at a higher level by the year 1990. It is inter-
esting to note that this type of model formulation results in
oscillations in the money supply as can be seen from Fig. 29b.
There seems to be an upturn just after the recession of 1960
and again in the late sixties until 1972. This kind of fluc-
tuating behavior in the economic system is well known. This
oscillation may also have been caused by the initial state of
the system.

In Fig. 30 are presented results for doubling the initial
storage of fossil fuels and seeing the responses for two dif-
ferent rates of inflation for the price function, P_1. The
structure and populations do not grow as much as would be
anticipated and this is attributable to a limited supply of
money.

Energy-Economic Calculations

This section brings together the systems of man and
nature through the common denominator of energy. As explained
in the Methods section it is theoretically possible to convert
the useful work of natural systems and human systems to a
common denominator of Fossil Fuel Work Equivalents (FFWE).
To this end, areas of different systems in Dade County have

been measured or calculated. This allows a budget of all these flows to be constructed.

Fossil-Fuel and Money Flows

Close inspection of the table of data in Appendix I shows the use and breakdown of fossil fuels from 1950 to 1972. For clarity the distribution of fossil fuels has been illustrated in Fig. 31 with pie diagrams for the years 1950, 1960 and 1972. It can be seen that high quality electrical energy has increased percentagewise while liquid fuels and gasoline have decreased. Notice that gasoline has gone from 45.5% of the fossil fuels used in 1950 to 29.5% in 1972.

The main money flows for 1972 in the Miami-Dade system are summarized in Table 9. These numbers were obtained from the various references cited in the data section and in Appendix I. The notes to Table 9 detail the calculations used to arrive at the value of the flows.

Subsystems of Dade County

Following from the Center for Wetlands, University of Florida, study of South Florida, Table 10 was constructed to give values for areas of different systems (see Fig. 32b). As can be seen from the table, the top seven categories are man-made systems, the next three are agricultural, and the rest are natural, self-maintaining systems. It can be seen that the overwhelming majority of land is covered by marsh or wet prairies. The areas were calculated by planimetering

Fig. 31. Pie diagrams illustrating the distribution
          of fossil fuels for 1950, 1960, and 1972.

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TOTAL= 11.24 x 10^{12} KCAL

1950

TOTAL= 32.58 x 10^{12} KCAL

1960

TOTAL = 73.63 x 10^{12} KCAL
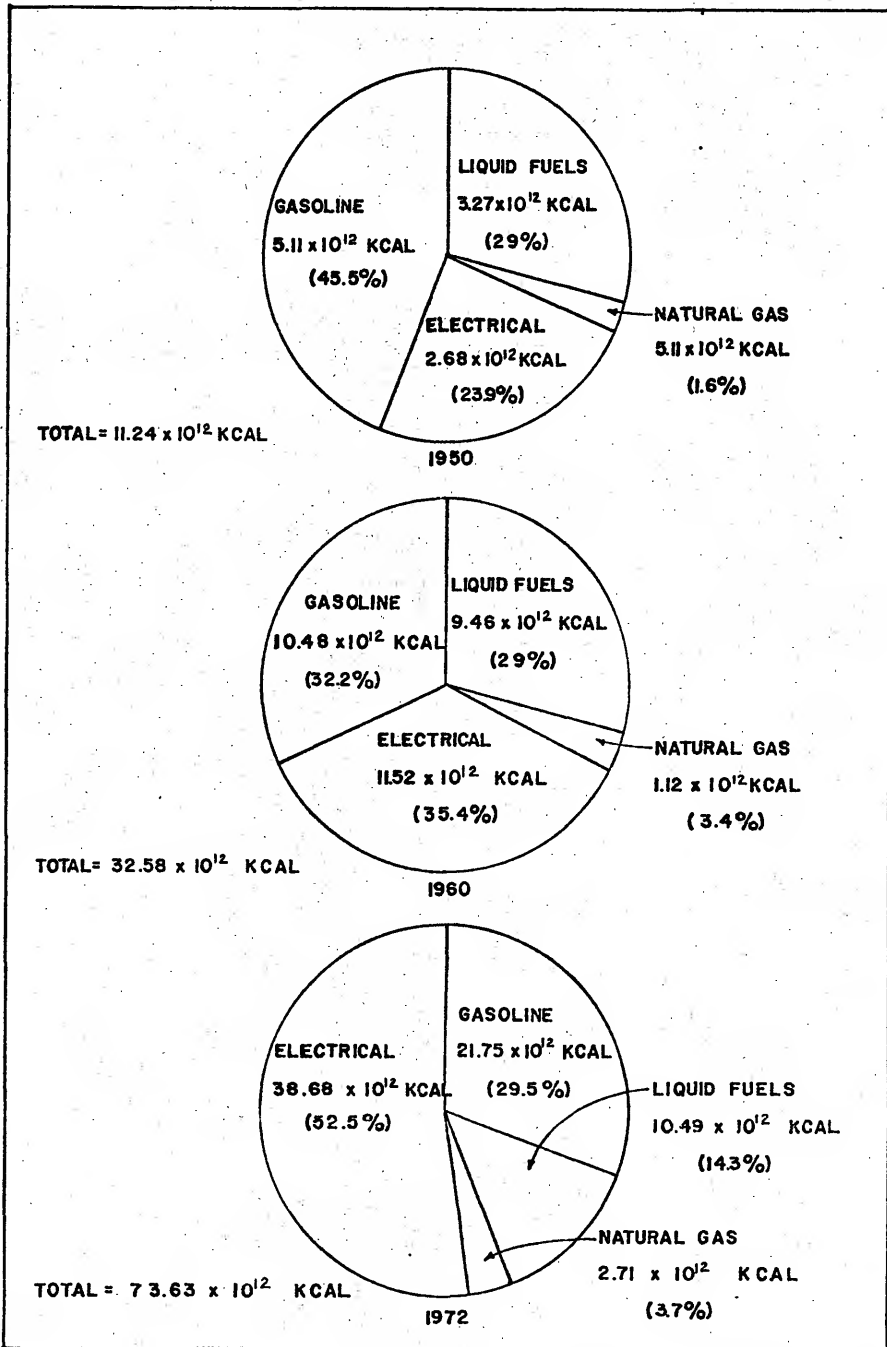
1972

Table 9

Major Money Flows in the Miami-Dade Urban System for 1972

Major Incomes, Billions of Dollars		Major Expenses, Billions of Dollars	
Tourism[a]	3.23	Expenditures for Fuels[g]	0.59
Government Subsidies[b]	0.856	Expenditures for Goods[h]	3.6
Transfer Payments[c]	0.62	Expenditures for Food[i]	1.25
Property Income[d]	0.79	Taxes[j]	1.36
Manufacturing[e]	2.0	Total	6.8
Agriculture[f]	0.14		
Total	6.65		

[a]Tourists spent $3 billion in 1970 (see Table 6, pathway no. 6). Multiply this by ratio of population in 1972 to 1970 to obtain approximate figure for 1972:

$$\$3 \times \frac{1.3676}{1.267} \text{ billion} = \$3 \times 1.079 \text{ billion} = \$3.23 \text{ billion}$$

[b]Multiply government subsidies in 1970 (see note 7, Table 6) by 1.079 to obtain $.856 billion for 1972.

[c]See note 6, Table 6.

[d]See note 6, Table 6.

[e]This was the approximate value of industry shipments (Florida Statistical Abstract, 1973).

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Footnotes to Table 9 - continued

  f Agricultural income accounted for approximately 2% of the total income (Buchanan, 1973).

    g See note 14, Table 6.

    h Money spent for vehicles was approximately $2.6 billion (see note 11, Table 6). Money spent for manufacturing goods was approximately $1.02 billion (Florida Statistical Abstract, 1973). The sum of these two is $3.6 billion.

    i See note 12, Table 6.

    j See note 8, Table 6.

Table 10

Land Areas Within Dade County
in Units of Square Kilometers[a]

	Area	Percent of Total
Power Plants	17	.31
Man-made Lakes & Reservoirs	12	.22
Cleared and/or Prepared with Roads	26	.47
Open Space and Recreation	71	1.3
Transportation Terminals	28	.51
Commercial, Industrial & Institutional	76	1.39
Residential	461	8.4
Orchards, Groves and Treecrops	8	.15
Vegetable Crops	335	6.11
Improved Pasture	69	1.26
Rivers, Streams and Lakes	50	.9
Fresh Water Marsh/Sloughs	1229	22.42
Salt Water Marsh	30	.55
Mangroves	302	5.51
Pinelands	217	3.96
Cypress Trees	108	1.97
Hardwood Trees	60	1.09
Sawgrass Marsh	551	10.05
Exposed Marl Prairies & Salt Flats	43	.78
Wet Prairies	1290	23.53
Estuary (Biscayne Bay)	499	9.12
Total	5482	100.00

[a]Planimetered from aerial photographs flown January, 1973 (Mark Hurd. Black and White Infrared and NASA False Color Mosaic U-2. Scale: 1 inch = 2 miles).

Fig. 32a. Aerial map of Miami-Dade County.

Fig. 32b. Land use map* of the Miami-Dade urban region
          derived from aerial photograph. The key to
          the map is as follows:

1 Cleared Land	14 Pinelands
2 Lakes & Reservoirs	15 Hardwoods
3 Recreation; Open Space	16 Rivers & Lakes
4,5 Residential	17 Cypress
6 Commercial & Industrial	18 Wet Prairie
7 Transportation	19 Scrub Cypress
8 Power Plants	20 Fresh Water Marsh
9 Pasture	21 Sawgrass Marsh
10 Vegetable Crops	22 Beach & Dune
11 Tree Crops	23 Salt Flats
12 Sugar Cane	24 Estuarine Bays
13 Dry Prairie	25 Salt Water Marsh
	26 Mangroves

*Land use map constructed by Bob Costanza,
Center for Wetlands, University of Florida.

Table 11

Major Energy Flows in Dade County for 1972

Name of Energy Flow	(A) Area of System[1] in 10^6 sq.meters	(B) Annual Work of that Type[2] 10^3 Kcal/m^2/yr	(C) Energy Concentration Factor[3]	(D) County's Annual Work[4] 10^{12} Kcal/yr	(E) Dollar Equivalent for Human Work[5] 10^6 \$/yr
Flows of Metabolic Work by Natural Ecosystems					
Fresh Water Marsh, Sawgrass Marsh[6] and Wet Prairies	3070.0	67.3	20.0	10.33	413.0
Salt Water Marsh and Marl Prairies[7]	73.0	34.6	20.0	0.13	5.2
Rivers, Streams & Lakes[8]	50.0	4.6	20.0	0.013	0.52
Pinelands[9]	217.0	11.5	20.0	0.12	4.99
Cypress Hardwoods[10]	108.0	20.0	20.0	0.11	4.4
Hardwoods[11]	60.0	38.3	20.0	0.11	4.4
Estuary (Biscayne Bay)[12]	499.0	20.0	20.0	0.5	20.0
Mangroves[13]	302.0	29.5	20.0	0.45	18.0
Subtotal				11.76	470.5

Table 11 - Continued

Name of Energy Flow	(A) Area of System[1] in 10^6 sq.meters	(B) Annual Work of that Type[2] 10^3 Kcal/m^2/yr	(C) Energy Concentration Factor[3]	(D) County's Annual Work[4] 10^{12} Kcal/yr	(E) Dollar Equivalent for Human Work[5] 10^6 $/yr
Other Contributing Natural Flows					
Tides in Biscayne Bay[14]	499.0	0.32	0.3	0.53	21.2
Beach Wave Energy[15,16]	1.75	516.0	1(?)	0.9	36.2
Wind Energy Dissipated to Ground[17]	5482.0	0.21	3(?)	0.38	15.3
Potential Energy of Water[18]	4983.0	0.0018	0.3	0.03	1.2
Potential Energy of Fresh/ Salt Water Concentration Gradient[19]	5482.0	9.14	10.0(?)	5.0	200.0
Subtotal				6.81	272.7
Nature's Metabolic Work on Managed Areas					
Improved Pasture[20]	69.0	21.8	20.0	0.08	3.2
Vegetable Crops[21]	335.0	12.8	20.0	0.22	8.6
Orchards, Groves, and Tree Crops[22]	8.0	14.1	20.0	0.006	0.24
Subtotal				0.31	12.0
Total Natural Energies				18.88	755.2

Table 11 - Continued

Name of Energy Flow	(A) Area of System1 in 10^6 sq.meters	(B) Annual Work of that Type2 10^3 Kcal/m^2/yr	(C) Energy Concentration Factor3	(D) County's Annual Work4 10^12 Kcal/yr	(E) Dollar Equivalent for Human Work5 10^6 $/yr
Fossil Fuel and Economic Flows					
Fuel Flows23					
Electricity			0.25	38.68	1547.0
Gasoline			1.0	21.75	870.0
Natural Gas			1.0	2.71	108.0
Liquid Fuels			1.0	10.49	420.0
Total Fossil Fuels				73.63	2945.0

NOTE: Notes 1 through 23 are contained in Appendix II. These notes show detailed calculations.

Fig. 33.   Diagram showing major energy and economic flows for Dade County.

TOURISM

AGRICULTURAL SALES

MANUFACTURING SALES

$3.23

$.14

STRUCTURE

$2.

92.5 kcal

MONEY $2.92

TAXES $1.36

SUBSIDIES $1.48

GOV'T

$3.60

GOODS

$1.25

1.5 kcal

FOOD

$.59

FUELS

NATURAL 73.6 kcal

18.88 kcal

ENERGIES
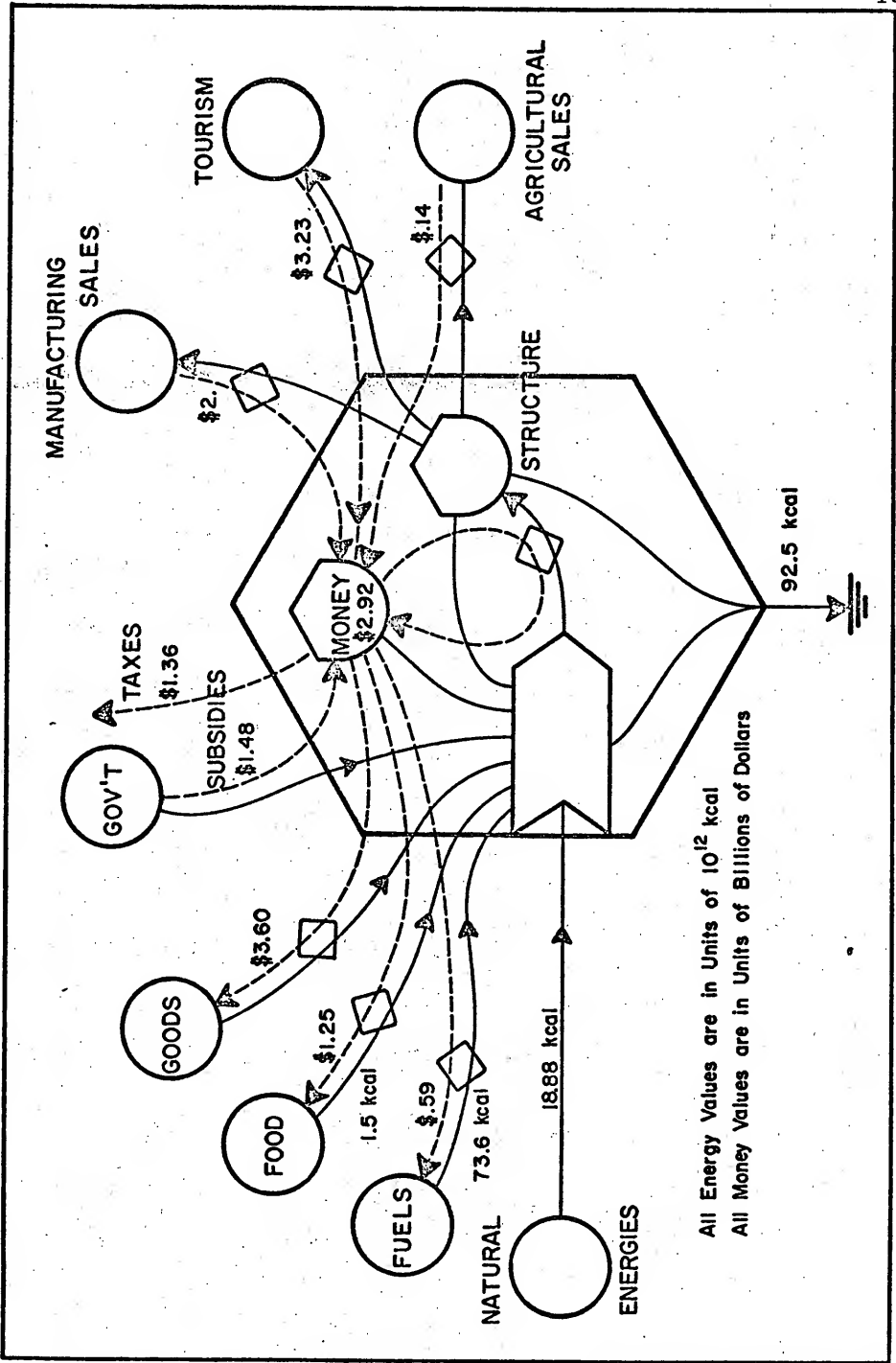
All Energy Values are in Units of 10^{12} kcal
All Money Values are in Units of Billions of Dollars

Everglades on the west, is bounded by the shoreline on the south, and extends several miles into Biscayne Bay on the east.

Natural to Fossil Fuel Energy Ratio

If all energies are put in units of Fossil Fuel Work Equivalents, then the ratio of natural to fossil fuel energies can be a measure of the extent of development in a region. Specifically, the ratio

$$\frac{\text{Total Work}}{\text{Fossil Fuel}} = \frac{\text{Fossil Fuel} + \text{Natural}}{\text{Fossil Fuel}} = 1 + \frac{\text{Natural}}{\text{Fossil Fuel}}$$

has a minimum value of one for no natural energies and attains high values for small fossil fuel flows. If the ratio is high for a region in comparison to neighboring regions, then more natural energies are available to subsidize investments of fossil fuel development. The ratio for Dade County since 1950 is tabulated in Table 12, where it can be seen that it has dropped significantly during the last twenty years. The overall ratio for the United States is approximately 1.4 (Odum, 1974; Kylstra, 1974). Approximate ratios for the United States are also included in Table 12 for comparison with the Miami region. The approximate ratio for Florida is approximately 1.25 while that for the region of South Florida is about 1.4 (Fontaine and Brown, 1975).

Table 12 is of immense interest since it can be seen that the ratio for Dade County and the United States were approximately equal in 1960. In about 1966-67 Dade County began to have sharp increases in budget, taxes, and fossil

Table 12

Fossil Fuel Energy, Total Natural Energy
and Their Ratio from 1950 to 1972[a]

Year	Natural Area,[b] Square Kms	Primary Production,[c] 10^{12} Kcal/yr	Other Natural Energies,[d] 10^{12} Kcal/yr	Total Natural Energies,[e] 10^{12} Kcal/yr	Fossil Fuels,[f] 10^{12} Kcal/yr	Fossil Fuel+Natural / Fossil Fuel Dade County[g]	United States[h]
1950	5180	13.05	6.81	19.86	11.2	2.77	1.78
1960	4940	12.45	6.81	19.26	32.6	1.6	1.6
1970	4824	12.16	6.81	18.97	64.3	1.3	1.4
1972	4790	12.07	6.81	18.88	73.6	1.26	1.37

[a]All energy units in FFWE (see Table 1).

[b]Computed as total area in Table 10 minus developed area given in Table 5.

[c]See Table 11. This is the sum of metabolic work on natural ecosystems plus managed areas. An average productivity of

$$\frac{12.07 \times 10^{12} \text{ Kcal/yr}}{4.79 \times 10^9 \text{ m}^2} = 2.52 \times 10^3 \text{ Kcal/m}^2/\text{yr}$$

was calculated for 1972 and this number was used to calculate photosynthetic production in each year knowing the natural land area.

[d]See Table 11. These energies include such things as winds and tides.

[e]This is the sum of primary production and other natural energies.

Footnotes to Table 12 - continued

^{f}See Table 20 in Appendix I.

^{g}The fossil fuels used in this ratio are the energy value in FFWE of the fossil fuels consumed. It assumes that the energy value of goods and services coming into the system is equal to the energy value of the goods and services flowing out. Another way of calculating this ratio is to include the energy value of the bought goods and services by multiplying this dollar flow by 25000 Kcal/dollar. It is assumed that only imports and not exports should be included in the determination of external selling price (see Fig. 37). Calculated in this way the ratio for 1972 would have been

$$\text{Ratio} = 1 + \frac{\text{Natural}}{\text{Fossil fuel}+\$(\text{fossil fuel}+\text{goods}+\text{food})\times 25000 \text{ Kcal/dollar}}$$

$$\text{Ratio} = 1 + \frac{18.88}{73.6+(.59+3.6+1.25)\times 25}$$

$$\text{Ratio} = 1.09$$

which indicates that Dade County is still less competitive than South Florida.

^{h}As calculated by Kylstra (1974) this ratio is total fossil fuels in the U.S. plus natural energies divided by fossil fuels. It was assumed that this ratio is the value that an average subregion of the country, in competition with Dade County, would have.

fuel energy use, which may be signs of the increasing costs
of overdevelopment. Thus, the time-delay for this ratio to
affect the system may be on the order of six or seven years.
The theory behind this ratio is further discussed in the
Discussion section.

Recycle of Energy from Urban Wastes

There has been much discussion recently of using garbage
as a means of tapping extra energy. With this in mind, a
calculation was made of the possible energy potential of the
urban refuse produced in Dade County if it is incinerated and
the heat energy derived from the organic matter used as fuel
in electrical power plants. An estimate of the organic urban
refuse produced in 1971 for the United States was .63 tons/
person/yr (Anderson, 1972). It was estimated that solid waste
can produce 2.52×10^6 Kcal/ton of energy (Hirst, 1973), so
that the energy that could be produced in Dade County amounts
to .63 tons/person/yr x 1.37×10^6 people x 2.52×10^6 Kcal/
ton = 2.18×10^{12} Kcal/yr. The energy cost of solid waste
collection, transportation, and disposal is approximately
$.076 \times 10^6$ Kcal/ton x .63 tons/person/yr x 1.37×10^6 people
= $.066 \times 10^{12}$ Kcal/yr, while the energy cost of incineration
is approximately 10 kwh/ton x 860 Kcal/kwh x 1.37×10^6 people
x .63 x 4 Kcal FFWE/Kcal(electrical) = $.03 \times 10^{12}$ Kcal/yr.
Thus, the net energy of the process is $(2.18-.066-.03) \times 10^{12}$
Kcal/yr = 2.08×10^{12} Kcal/yr. In comparison to the total
fossil fuel energy use in Dade County for 1972, it amounts to
2.7% of the total.

The above calculation assumes that the garbage collection system will remain as it is with the exception that the garbage will be used for generating energy rather than landfill. As the energy level of the system gets lower, garbage, and therefore potential recycle, will be reduced. At some level will garbage collection be drastically curtailed? In order to do a complete net energy analysis of garbage collection the money expenses and their associated energy costs would also have to be included. Then a comparison to alternative methods of recycle could be made.

Food Production

Looking at Table 11, it can be seen that the total agricultural output amounts fo 4.4 x 10^{12} Kcal/yr or vegetable crops and groves. If it is assumed that the net productivity is 50% and that 20% of this is edible, then .44 x 10^{12} Kcal/yr is available for consumption (E. P. Odum, 1971). Since 1.5 x 10^{12} Kcal/yr of food is needed for the county, of which 1.3 x 10^{12} Kcal/yr is carbohydrate, these crops can supply approximately one-third of the carbohydrate requirements of the Dade County population.

The total gross production of improved pasture amounts to 1.6 x 10^{12} Kcal/yr (see Table 11). Assuming that net production is 50% of this and that the conversion into beef results in a 10% conversion, the protein production was calculated to be .08 x 10^{12} Kcal/yr. An average person needs approximately 600 Kcal of protein per day, which makes for a

requirement of $.3 \times 10^{12}$ Kcal/yr of protein for the Dade County population, and which is approximately four times as much as can be produced within the county.

Energy to Money Ratios Expressed in Energy Units

Many ratios may be of interest for a theoretical and conceptual understanding of the function of urban regions. One of these is the ratio of total direct energy use (fossil fuel + natural) to the gross regional product. In 1972 this ratio for Dade County was 92.5×10^{12} Kcal/$(1.25 \times \$5.45 \times 10^{9})$ = 13580 Kcal/dollar (gross regional product = 1.25 times the expenditures for goods and services; see Brown, 1973). This ratio can be compared to the ratio of the total energies of the U.S. to its gross national product. This ratio was 25000 Kcal/dollar. The lower ratio for Dade County indicates that more dollars are generated per unit of fossil fuel consumed. This may be characteristic of high consumer and service oriented economies whereas industrial areas may have a high energy to dollar ratio. This ratio might be used as an index for comparison of urban systems.

The actual energy value of the food consumed in the system is fairly small but the money spent was approximately $1.25 billion. If this is converted to energy expended somewhere else in the country by the 25000 Kcal/dollar ratio, it is seen that 31.2×10^{12} Kcal of energy are required to deliver the food to the urban region. The ratio of this to the total energy flow is .34.

The Role of Solar Energy Technology
in the Miami-Dade Urban System[1]

Energy Calculations for Water Heaters

In order to evaluate and compare competing water heating
systems such as solar, natural gas, electrical, and wood, all
energy subsidies to each of the systems must be identified
and quantified. Much ado about solar energy as a new energy
source has been made recently. The only way to decide this
issue is to determine how much fossil fuel subsidy is required
to make a solar device operate as compared to competing fossil
fuel systems. Not only are energy flows quantified in this
section, but so also are capital requirements.

Located in one of the most southern areas of the United
States with an average incident solar radiation flux of 4500
Kcal/m^2/day (Bennett, 1965), the Miami-Dade County region is
a desirable area for evaluating the effectiveness of solar
energy technology. Presented in Figs. 34 and 35 are two dia-
grams illustrating the main pathways involved in solar, elec-
tric, and gas water heaters (Odum, 1975). The size of the
water heaters and the flows are those which would be neces-
sary for an average family of four under the present standard
of living. The solar water heater uses incident solar energy
coupled with large area collectors to heat water. The manu-
facture of equipment for storage and collection required
fossil fuel energy in the main U.S. economy as an initial

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[1]Done in collaboration with Sandra Brown, Department of
Environmental Engineering Sciences, University of Florida.

investment. This is depicted as pathway 10 in Fig. 34. The only other fossil fuel energy necessary for running this system is electricity for an electric immersion heater during the months of low solar radiation (pathway 6 in Fig. 34).

The electric and gas water heater systems use electrical and natural gas energy, respectively, to heat water. Initial equipment also requires fossil fuels in the main U.S. economy for manufacture (pathway 10 in Fig. 35). The initial investment for the solar heater is greater than for the electric or gas heaters but less fossil fuel is used directly. Tables 13 and 14 describe the flows in Figs. 34 and 35 with notes detailing the calculations. Dollar costs were converted to fossil fuel energy costs through the conversion factor of 25000 Kcal/dollar (see Table 1).

Calculations based on the flows in Figs. 34 and 35 were made to assess the fuel savings and capital savings of replacing electrical and gas heaters with solar water heaters in the Miami-Dade region. The results are summarized in Table 15. It can be seen that both systems result in a savings of fossil fuel energy. Fuel savings offset capital requirements if a solar water heater is used instead of an electrical system, resulting in a net capital savings. On the other hand, even though a solar heater uses less energy than a gas heater, the difference is small and loss of capital would be incurred if gas were replaced by solar.

Table 16 presents the results of calculations assuming that all the electrical water heaters were replaced in Dade

Fig. 34. Major energy and money flows for a solar water heater. Pathway numbers in circles refer to numerical values and footnotes in Table 13. (From S. Brown and J. Zucchetto, unpublished paper.)

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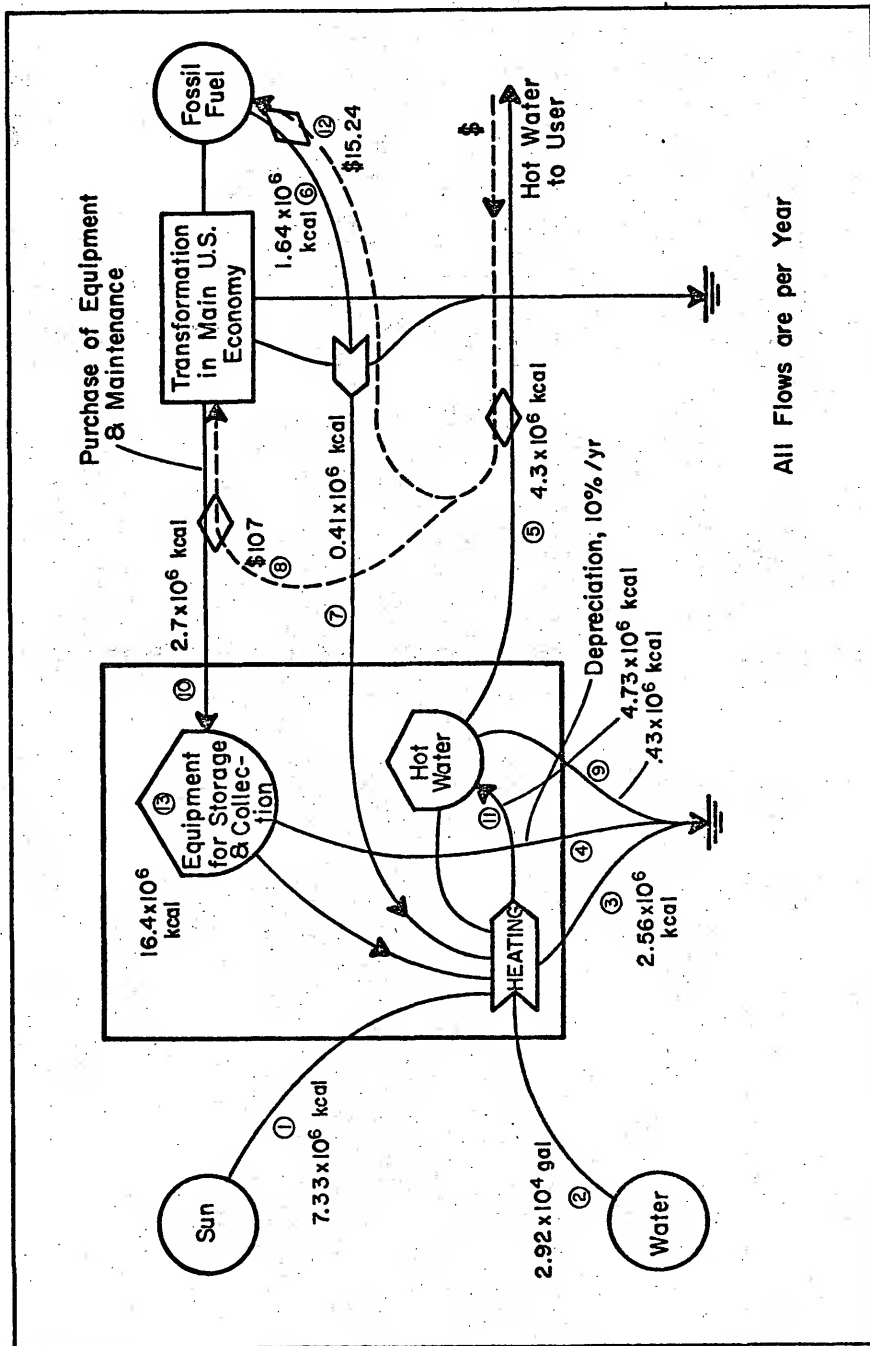
All Flows are per Year

Table 13

Flows and Storages for Solar Water Heater
for a Family of Four in Dade County

Pathway on Fig. 34	Note[a]	Description	Numerical Value	Reference
1	1	Average Incident Solar Radiation on 4.46 m^2 Collector	7.33×10^6 Kcal/yr	Bennett, 1965
2	2	Annual Cold Water Consumption	2.92×10^4 Gal/yr	
3	3	Losses Due to Inefficiency of Solar Heater	2.56×10^6 Kcal/yr	Aimone, 1974
4	4	Depreciation of Solar Equipment	10%/yr	Solar Water Heater Co., Miami, Fla.
5	5	Heat Energy for Hot Water	4.3×10^6 Kcal/yr	
6	6	Fossil Fuel Needed to Heat Water	1.64×10^6 Kcal/yr	
7	7	Electrical Energy Needed	$.41 \times 10^6$ Kcal/yr	
8	8	Initial and Maintenance Costs of Equipment Prorated Over 10 Years	$107/yr	
9	9	Loss of Heat from Tank	$.43 \times 10^6$ Kcal/yr	
10	10	Energy Cost for Equipment	2.7×10^6 Kcal/yr	Ibid.
11	11	Energy Needed for Heating Water	4.73×10^6 Kcal/yr	
12	12	Cost of Fuel	$15.24/yr	Florida Power & Light Corp.
13	13	Cost of Solar Equipment	16.4 or 20×10^6 Kcal/yr	

[a]Notes are contained in Appendix II.

Fig. 35. Major energy and money flows for an electrical and natural gas water heater. There are pathways which have two numerical values associated with them: the first number refers to an electrical water heater whereas the second one refers to a gas water heater. Pathway numbers in circles refer to numerical values and footnotes in Table 14. (From S. Brown and J. Zucchetto, unpublished paper.)

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All Flows are per Year
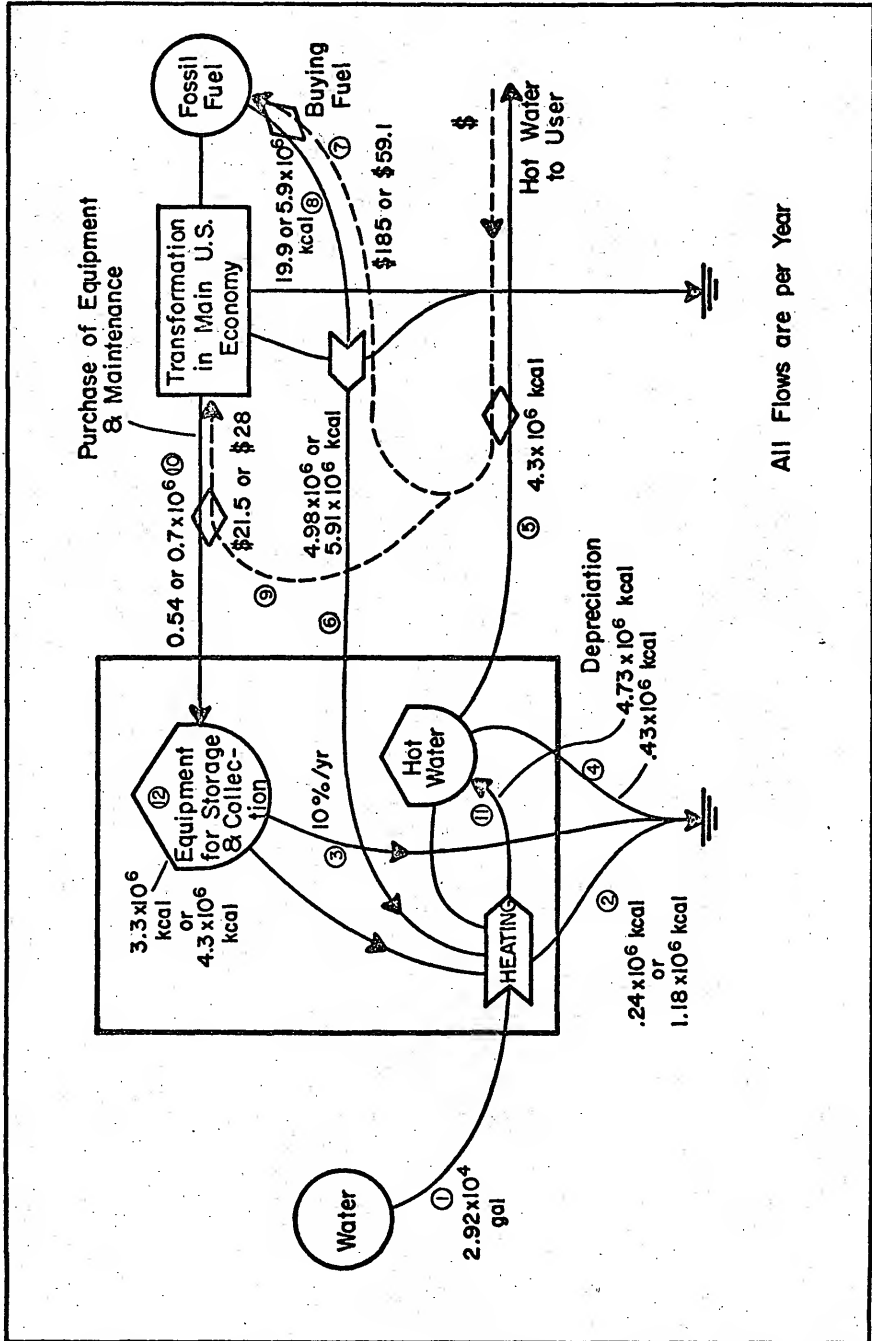
Table 14

Flows and Storages for Electric and Gas Water Heaters
for a Family of Four

Pathway on Fig. 35	Note[a]	Description	Numerical Values for Electric Heater	Numerical Values for Gas Heaters
1	1	Annual Cold Water Consumption	2.92×10^4 Gal/yr	2.92×10^4 Gal/yr
2	2 & 13	Heat Loss Due to Inefficiency of Heater	$.24 \times 10^6$ Kcal/yr	1.18×10^6 Kcal/yr
3	3	Depreciation of Equipment	10%/yr	10%/yr
4	4	Heat Loss from Tank	$.43 \times 10^6$ Kcal/yr	$.43 \times 10^6$ Kcal/yr
5	5	Heat Energy for Hot Water	4.3×10^6 Kcal/yr	4.3×10^6 Kcal/yr
6	6 & 14	Electrical Energy Use or Natural Gas Use	4.98×10^6 Kcal/yr or 5.79×10^3 Kwh/yr	5.91×10^6 Kcal/yr
7	7 & 15	Cost of Electricity or Natural Gas	$185.3/yr	$59.1/yr
8	8 & 14	Fossil Fuel Needed to Heat Water	19.9×10^6 Kcal/yr	5.91×10^6 Kcal/yr
9	9 & 16	Cost of Equipment	$21.5/yr	$28/yr
10	10 & 16	Energy Cost for Equipment	$.54 \times 10^6$ Kcal/yr	$.7 \times 10^6$ Kcal/yr
11	11	Number of Kcal Needed for Producing Hot Water	4.73×10^6 Kcal/yr	4.73×10^6 Kcal/yr
12	12 & 17	Cost of Equipment (Total Initial Cost)	3.3×10^6 Kcal	4.3×10^6 Kcal

[a]Notes are contained in Appendix II.

Table 15

Difference in Per Capita Fossil Fuel and Capital Expenditures
Between Solar Water Heaters and Electrical
or Gas Water Heaters for Dade County

	Fuel Savings, 10^6 Kcal/capita/yr	Savings in Fuel Expenditures, $/capita/yr	Capital Outlay Required, $/capita/yr	Net Capital Savings, $/capita/yr
1) Solar Water Heater vs. Electric Water Heater	4.57[a]	34.7[b]	21.4[c]	13.3[d]
2) Solar Water Heater vs. Gas Water Heater	1.07[e]	10.7[f]	19.8[g]	-9.1[h]

[a] The actual fuel savings of a solar heater over an electrical heater in Dade county would be pathway 8 in Fig. 35 for an electrical heater minus pathway 6 in Fig. 34 which amounts to

$$\frac{(19.9-1.64)\times10^6 \text{ Kcal/yr}}{4 \text{ people}} = 4.57\times10^6 \text{ Kcal/capita/yr.}$$

[b] Savings in fuel expenditures is the fuel saved multiplied by an average cost for 1974 per Kcal for fossil fuel in Dade county or

$$4.57\times10^6 \text{ Kcal/capita/yr} \times \$.76\times10^{-5}/\text{Kcal} = \$34.7/\text{capita/yr.}$$

[c] The difference in cost between solar and electric water heaters is pathway 8 in Fig. 34 minus pathway 9 in Fig. 35 or

$$\frac{(\$107-\$21.5)/\text{yr}}{4 \text{ people}} = \$21.4/\text{capita/yr.}$$

Footnotes to Table 15 - continued

dNet capital savings is the amount of money saved in fuel expenditures minus the capital outlay required or

$34.7-$21.4 = $13.3/capita/yr.

eThe actual fuel savings of a solar heater vs. a gas heater in Dade county would be pathway 8 in Fig. 35 for a gas heater minus pathway 6 in Fig. 34 for a solar heater or

$$\frac{(5.91-1.64)}{4 \text{ people}} \times 10^6 \text{ Kcal/yr} = 1.07 \text{ Kcal/capita/yr.}$$

fSavings in fuel expenditures is the fuel saved multiplied by the price or

1.07×10^6 Kcal/capita/yr x $1.\times10^{-5}$/Kcal = $10.7/capita/yr.

gThe difference in capital outlay is the cost of a solar water heater minus the cost of a gas heater or pathway 8 in Fig. 34 minus pathway 9 in Fig. 35 or

$$\frac{$(107-28)}{4 \text{ people}} = $19.8/capita/yr.$$

hNet capital savings is savings in fuel expenditures minus capital outlay required. In this case there are no savings but a net deficit which is

$(10.5-19.8)/yr = -$11.8/capita/yr.

Table 16

Fossil Fuel Savings and Capital Expenditures for the
Replacement of Electric Water Heaters by Solar Water Heaters
Over a Ten-Year Period in Dade County[a]

	Fuel Savings,[b] 10^{12} Kcal/yr	Savings in Fuel Expenditures, 10^6/yr	Capital Outlay Required, 10^6/yr	Net Capital Savings,[c] 10^6/yr
1) Solar Water Heaters Installed Over a Period of 10 Years. Prices Assumed to Remain Constant.	2.6	19.8[d]	12.1[e]	+7.7
2) Solar Water Heaters Installed Over a Period of 10 Years. Inflation Rate Assumed to be 10%/yr.	2.6	35.[f]	17.35[g]	+17.65

[a] Two cases are considered: 1) Prices remain constant over a 10-year period and 10%/yr of the population is provided with solar equipment. 2) Prices inflate at the rate of 10%/yr and 10%/yr of the population is provided with solar equipment. For both cases it was assumed that the population remains at the level of 1.36×10^6 people. Since approximately 75% of Dade county households (Fla. Statistical Abstract, 1973) use electricity for water heating, the number of people affected is $.75 \times 1.36 \times 10^6 = 1.02 \times 10^6$ people.

[b] If it were possible to instantaneously replace all the electric water heaters by solar water heaters then the actual fuel savings in Dade county would be pathway 8 in Fig. 35 minus pathway 6 in Fig. 34 which amounts to

Footnotes to Table 16 - continued

$$\frac{(19.9-1.64)x10^6 \text{ Kcal/yr}}{4 \text{ people}} = 4.57x10^6 \text{ Kcal/person/yr.}$$

Since it is assumed that 10% of the system for heating water is replaced each year the total fuel savings the first year would amount to

.1x4.57 Kcal/person/yr x 1.02x10^6 people = .46x10^{12} Kcal.

The second year fuel savings would amount to .93x10^{12} Kcal and savings would increase each year until the 10th year. The total savings over the 10-year period amounts to 25.6x10^{12} Kcal for an average of 2.6x10^{12} Kcal/yr.

^{c}Net capital savings is the amount of money saved in fuel expenditures minus the capital outlay required.

^{d}The savings in money spent for fuel would be (see Table 6, note 15)

2.6x10^{12} Kcal/yr x \$.76x10^{-5}/Kcal = \$19.8x10^6/yr.

^{e}The difference in cost between solar and electric water heaters is pathway 8 in Fig. 34 minus pathway 9 in Fig. 35 or \$(107-21.5)/yr or dividing by a family of four to get \$21.35/person/yr. This number assumes an interest rate of 10%/yr, an equipment lifetime of 10 years and 1974 prices. In the first year .1x\$21.35x1.02x10^6 people = \$2.2x10^6 would have to be provided. The second year would require twice as much since the heaters bought in the first year are still being paid for plus 10% new heaters are added. This would continue for each year and the total money expended over 10 years would be

$$\sum_{n=1}^{10} \$2.2x10^6 \ n = \$121x10^6$$

or an average of \$12.1x10^6/yr. Much more money would be spent in the last few years than at the beginning. After this 10-year period is over there would still be money left to pay remaining from the loans for the last 9 years of the period. This would amount to

$$\sum_{n=1}^{9} \$2.2x10^6 \ n = \$99x10^6$$

or an average of \$11x10^6/yr for a period of 9 years after the initial 10-year installation period.

Footnotes to Table 16 - continued

^{f}Savings in fuel the first year are $.46 \times 10^{12}$ Kcal (see footnote b), which amounts to

$$.46 \times 10^{12} \text{ Kcal} \times \$.76 \times 10^{-5}/\text{Kcal} = \$3.5 \times 10^6.$$

The second year twice as much fuel would be saved at a price 10% higher which would amount to

$$.92 \times 10^{12} \text{ Kcal} \times \$.836 \times 10^{-5}/\text{Kcal} = \$7.76 \times 10^6.$$

Continuing in this way for 10 years the total money saved is $\$350.6 \times 10^6$ for an average of $\$35. \times 10^6/\text{yr}$.

^{g}If the initial cost rises by 10% each year then the money paid each year will be $\$2.20 \times 10^6$ the first year (see footnote d), $\$(2.42+2.2) \times 10^6$ the second year, $\$(2.84+2.42+2.2) \times 10^6$ the third year, etc., since each year's outlays are a summation of earlier plus present prices. The total amount expended over a 10-year period would be $\$173.5 \times 10^6$ for an average of $\$17.35 \times 10^6/\text{yr}$.

County over a ten-year period. Approximately three-quarters of the households in Dade County use electrical water heaters (Florida Statistical Abstract, 1973). Two cases were considered, namely, prices constant for ten years and prices increasing with a 10% per year inflation rate. It can be seen that fuel savings are realized and capital savings accrue. This quantity of fuel saved, however, still only represents about 3.5% of the total fossil fuel budget of the county.

Investment Alternatives to Water Heaters

The question now arises as to whether solar water heaters should be substituted for electrical heaters. What feedback and work contribution does hot water provide to a society by keeping its members clean? This function may not be necessary in a low energy society. Thus, if our society is to rapidly decline, putting capital and energy into water heaters will constitute a wasteful action. This money could be used to buy Middle Eastern oil, for example, and perhaps provide some competitive advantage to the United States.

To obtain a measure of comparison between several alternatives, divide the Kcal of heat output for each type of heater by the dollars invested. For the gas heater this ratio is 4.3×10^6 Kcal/\$87.1 = 49500 Kcal/dollar; for the solar heater this ratio is 4.3×10^6 Kcal/\$122.24 = 35200 Kcal/dollar; for the electrical heater this ratio is 4.3×10^6 Kcal/\$206.5 = 20800 Kcal/dollar. Now, if Middle Eastern oil is assumed to be \$12/barrel and there are 1.015×10^6

Kcal/barrel, then this oil has a value of 96000 Kcal/dollar.
The question then arises as to whether it would be economic-
ally and energetically more advantageous to purchase Middle
Eastern oil and use oil-burning water heaters or use the oil
for more directly productive activities.

At the individual level is also the question of discount
rate. If the energy level declines rapidly many individuals
may decide to invest in some part of the economy which is
growing rather than buying a new water heater. If it is
assumed that money can be earned at the rate of 5%/yr and the
cost of a new solar water heater is $800 (see Table 13, note
14), then an amount equal to $392 could be earned over ten
years for a family of four.

Tables 15 and 16 represent the savings in fuel within
Dade County, whereas work done outside the county is reflected
by dollar flows. If the energy requirements in the entire
U.S. economy are considered, the simple diagram in Fig. 36
may be drawn to show the relative magnitude of flows for each
system. Included in Fig. 36 is also the primitive wood-burn-
ing system for which wood is collected from a steady-state
forest and burned to heat water. It was assumed that this
forest grew at the rate of .1 gm/m^2/day and the energy value
of the wood was 4.5 Kcal/gm. The acreage necessary could
then be calculated.

It is seen that the issue of solar energy technology is
complex and even if the society has enough extra energy to
diversify into such a technology the savings in energy are

Fig. 36.   Diagram summarizing energy flows for four
            different types of water heaters.

            a.   Primitive solar water heater for which
                 wood is collected from a steady-state
                 forest. The only capital investment
                 is a small kettle or stove.

            b.   Modern solar water heater utilizing a
                 flat plate solar collector.

            c.   Natural gas water heater.

            d.   Electrical water heater.

            (From S. Brown and J. Zucchetto, unpub-
            lished paper.)

Primitive Wood Solar Heater
(a)

Modern Solar Heater
(b)

Natural Gas Heater
(c)

Electric Heater
(d)
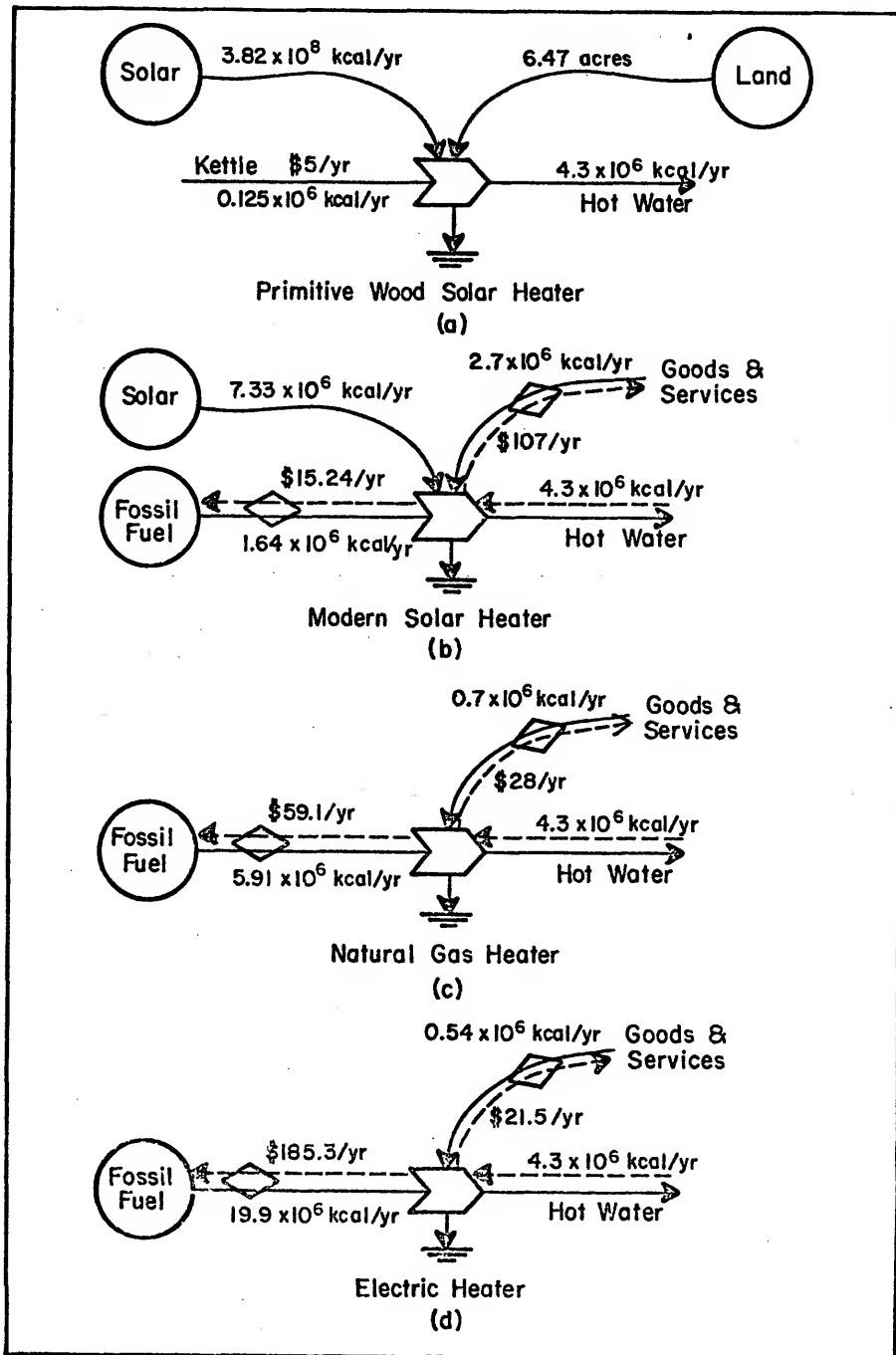
only a few percent. How fast the energy level of the system
declines will determine whether solar heaters will be used
on a wide basis.

DISCUSSION

This sections brings together in overview the results of
this dissertation and the implications and questions to which
they lead. Some of these include the nature of the models
presented, the effects of energy and price on the general
behavior of the urban variables, and some theoretical discus-
sion. Consideration of energy calculations including those
of natural, agricultural, recycled garbage, and solar energy
technology are considered. The future of Dade County in light
of these calculations is also discussed. The next few para-
graphs discuss the similarities between urban and natural
ecosystems.

Comparison Between Urban and Natural Systems

Theoretically, a system will build a mass-energy struc-
ture for internal and external interactions. The maintenance,
growth, and stability of these systems require the capture
of energy and mass from the outside. Based on this, models
of city systems can be constructed using storages and flows,
the flows being some function of external forcing functions
and internal storages and flows (see Fig. 3 for a description
of the components used for these models). Since this work
was derived from previous modeling directed towards natural

ecosystems, Table 17 has been constructed to point out the
similarities between natural ecosystems without man and human
systems. Both systems obey the conservation of energy and
mass, responding to external sources of these parameters.
Both systems need information and structure for control,
require maintenance, recycle structure, establish communica-
tion pathways, diversify, produce, consume, establish cycling
pathways, and exhibit successional development. Human systems
contain libraries and culture for information storage and
transmission, government, institutions and communications for
control, industry for production, and people for consumption.
Recycle of structure is accomplished through repair and re-
processing of materials. Successional development can be
seen taking place in neighborhoods with invasions of ethnic
groups and urban renewal programs. All of these processes
are energetically costly and must be constantly   maintained.
Money in the human system acts as the distribution mechanism
for energy, materials and information, and aids in keeping
the system alive and functioning, in the process establishing
cycles of money flow, balance of payments, and a basis for
exchange value (see sections on urban indicators and data for
a discussion and compilation of the variables which are a
measure of the properties discussed in the above paragraph).

Table 17

Similarities Between Natural Ecosystems and Urban Systems

Category	Natural Ecosystems	Urban Systems
Energy	Solar; Natural Energies	Solar; Natural Energies; Fossil Fuels
Materials	Nutrients; Trace Metals	Resources
Information	Genes; Chemical Systems	Genes; Memory; Libraries; Computers
Structure	Biomass	Square Feet of Buildings
Maintenance	Repair; Replacement	Repair; Replacement; Renewal
Entropy Generation	Death; Heat	Death; Depreciation; Heat
Diversity	Species	Occupations; Businesses; Ethnicity
Production	Photosynthesis	Industrial Production
Consumers	Animals; Microbes	Government; Industry; People
Cycles	Nutrients	Money
Temporal Processes	Succession; Climax	Succession of Neighborhoods; Urban Renewal; Steady-state

Effects of Available Fossil Fuel Energy

As in other sciences the axiom of the conservation of energy and mass has evolved through experience and is accepted as self-evident so then energy has been accepted in this dissertation as a primary forcing function for all human systems. This is a good assumption based on experience with our highly mechanized society (Odum, 1971). The high fossil fuel energy density (300 Kcal/m^2/day) necessary to support the variety of functions in the Miami-Dade urban system is necessarily dependent on sources of energy, especially fossil fuels. The availability of high quality electrical energy made possible the high density of structure in cities because of its cleanliness and versatility. In the lower density, residential parts of cities it has also made possible the use of a diversity of appliances which contribute to a high energy consumption per person. At present densities, lighting and heating skyscrapers with oil, coal, and gas would constitute a very dirty proposition in terms of releasing hydrocarbons to the city environment. Even the proposed uses of solar energy for heating and lighting would be prevented under high densities because of shading. Since almost 4 Kcal of fossil fuel energy are necessary to generate 1 Kcal of electrical energy (see Fig. 4), high density urban systems are necessarily dependent on large supplies of fossil fuels. The increasing use of electrical energy in the urban system is graphically shown in Fig. 31.

Since the entire urban system is so highly intercon-
nected and subsystems mutually dependent, several parameters
have been plotted as a function of total fossil fuel energy
driving the entire system in Figs. 13 and 14. The number of
telephones, effective buying income, and tourists seems to be
increasing in a piecewise linear manner. The curves of money
costs such as the budget and sales tax have increasing slopes
with increasing energies. This reflects the increasing costs
with size as is pointed out so well by Lamm (1973), who shows
the increasing costs of services as cities become larger.
The curve for retail sales has a plateau which corresponds to
leveling in the curves of effective buying income, budget,
number of telephones, sales tax, and building structure.
This decrease in activity compared to preceding years lasted
from an energy level of 58 to 64 x 10^{12} Kcal which corresponds
to the year 1969. Beyond the 64 x 10^{12} Kcal energy level the
curves begin to increase at a greater rate. Looking at Fig.
16 it can be seen that a pulse of energy entered the system
from 1969-70 followed by an increase in the rates of growth
for effective buying income, retail sales, number of tele-
phones, sales tax, and building structure. This is a nice
example of the influence of energy in the urban system.
Furthermore, the slowdown in growth during 1969 may have
been due to the decrease in the rate of energy use from 1968-
69 which can be seen in Fig. 16. Further discussion of corre-
lation between energy and urban variables can be found in the
Data section.

In Figs. 14b and 15 are graphs of the urban variables discussed above plotted as a function of the sum of gasoline and electrical energies. The units of energy in this case are expressed as actual Kcal of gasoline and electrical energy without conversion to Fossil Fuel Work Equivalents. Using electrical plus gasoline energy as the independent parameter suggested that these energies were more directly involved in the actual mechanical workings of the economy whereas petroleum oils and natural gas would be used for cooking and heating. Several of the curves such as number of telephones, total budget, and sales tax collections are almost perfectly piecewise linear while the other curves are approximately so. These graphs suggest the direct impact of fossil fuel energies on urban parameters.

The quantitative relationships for several urban parameters in Dade County can be seen in Table 3. Total energy increased 77% from 1963 to 1971. Those variables which increased in approximately the same proportion were number of telephones (67%), retail sales (78.5%), and building structure (76%), while those which increased in greater proportion were number of tourists (100%), effective buying income (107%), budget (130%), and sales tax (250%). Population increased by a smaller percentage (23.5%).

The previous discussion was based on actual data for the Miami-Dade urban system. In addition, consider the simulation models depicted in the Results section and the effect of different energy functions on the output of the models. The

model in Fig. 20 shows the city system being driven by a
storage of fossil fuels representing the proven fossil fuel
reserves in the United States available to the residents of
Dade County. The characteristic curve of city structure is
one which starts out slowly in the beginning, goes through a
period of steep growth, peaks, and then begins to fall. This
can be seen in Figs. 21 and 22. The storage of fossil fuels
resembles an inverse sigmoid curve whose greatest rate of
decrease corresponds to the greatest rate of increase of the
structure curve.

Rather than a storage of fossil fuels the model in Fig.
24 depicts an urban model driven by an arbitrary outside
energy function and depreciation of structure assumed to be
a square function of structure. Three energy functions were
considered: linearly increasing after 1972; level after
1972; linearly decreasing after 1972. The increasing energy
function could represent a net nuclear energy technology.
For the energy increasing case structure peaks and then drops
slightly and levels off. The production of structure peaks
and then changes erratically. The case where energy levels
after 1972 shows a sharper peak in structure than the previous
case and one for which the production of structure peaks and
declines thereafter. The energy declining case results in
structure peaking and declining as does the production of
structure.

As a final consideration of the effect of fossil fuel
energy, the tourist model in Fig. 27 was simulated for two

initial values of fossil fuel energy, one being twice as
large as the other. This case was considered in order to
understand an increase in available energy due to a net
energy coal technology. Comparing Figs. 28a and 30a it is
seen that for prices increasing 20% per year, structure peaks
approximately 4% higher with initial fuel storage doubled.
This is smaller than would be expected and might be explained
by the fact that the model doesn't include increasing the
money supply in relation to the amount of available energy.
The decrease in tourism and the increase in prices combine to
limit the capital for growth. A sudden input of Federal sub-
sidies could result in a surge of growth followed by decline
as fuels were exhausted.

Effects of External Price

For the models simulated in the Results section, money
transactions with the outside world occur through the price
transactor, the mathematics for which is shown in Fig. 3.
It represents the fact that for every flow of energy, goods,
or services in the human system, there is a counter-current
flow of money. As depicted in the models in Figs. 19, 20,
24, and 27, the price is shown to be determined external to
the urban system, the net result of the complex interactions
in the U.S. and world economic systems. Since the early
fifties the western world has not been subjected to very
severe rates of inflation. Prices of energy have remained

fairly constant from 1950-72 (Minerals Yearbook) as have many other prices for basic goods which were all dependent on energy for their existence. However, as the reserves of fossil fuels become depleted, it becomes more expensive for a unit of energy to be delivered to where it is needed: a greater amount of capital and energy is required and this is reflected in the price system as an increase in the price of fuel. This increase in price is propagated through the economic system and affects the costs of goods and services. Rapidly increasing costs occurred for the prices of fuels in 1973 as the era of cheap and easily accessible fuels came to an end. The situation was aggravated by the fourfold increase in the price of Middle Eastern oil. Since these events the industrialized countries have been subjected to double-digit inflation.

In order to simulate this rapid inflation the price functions for some of the models were programmed to remain constant from 1950 to 1972 and then linearly increase from then on. Since the exact shape and magnitude of the future price function is unknown, simulations were conducted for several price functions. The effects of these are discussed in the following paragraphs.

Fossil Fuels

The storage of fossil fuels responds in a very interesting manner as can be seen from Fig. 23b. As the inflation rate (price) increases, the amount of fossil fuel remaining

in 1990 increases. This result seems to agree well with the notion of the price system regulating supply and demand forces. As prices increase more money is spent for goods, services, and fuels, leaving less money in storage for further spending: fewer kilocalories of fuel can be purchased with a dollar. The amount of fuel remaining in 1990 is not linearly related to the inflation rate, i.e., a 50% inflation rate does not result in five times as much fuel remaining as a 10% inflation rate.

Fuel Expenditures

As can be seen from Fig. 23c, fuel expenditures peak rather sharply in 1973 for a 50% inflation rate and then descend more rapidly than the other rates as the money supply is used up faster until it reaches a low level in 1990. There doesn't seem to be any general pattern to the curves except for an initial pulse of spending at the onset of inflation.

Money Supply

As would be expected, the money supply decreases with increasing prices as can be seen from Fig. 23a. This implies that there will be less capital for growth if a greater and greater proportion of money continues to go for fuels. This may be one of the primary limiting factors to growth that Dade County and other urban regions will experience.

Structure

The characteristic curve of structure changes as a func-
tion of the inflation rate (Fig. 22b). As the inflation rate
increases structure peaks earlier and at a lower level due to
the increasing costs and unavailability of capital for new
structure. This seems to be the current situation in the
United States in 1974 with high interest rates, lower pro-
ductivity, and falling GNP.

Population

As can be seen from the results of the tourist model in
Fig. 28c, increasing prices inhibit the growth of population
as well as the other storages in the system. The 1990 popula-
tion is decreased approximately 25% to a level of 1.6 million
people. This comes about because the model assumes that both
migration and reproduction are functions of energy supply,
structure, and money. In essence, this says that if there is
no growth of the city then population growth will also become
zero. By combining population growth to available energy as
in Fig. 27 a more realistic prediction method is obtained as
compared to extrapolation of population data into the future.

In general, then, the effect of increasing prices is to
inhibit the growth of the system and prolong the supply of
fossil fuel. The models seem to generate results which are
in agreement with notions of supply and demand.

Competitiveness of Miami-Dade County

In Table 12 the ratio of the total work for Miami-Dade
County to the fossil fuel work was tabulated from 1950 to
1972. The total work was considered to be composed of the
sum of natural energies and fossil fuel energies, where both
are expressed in units of Fossil Fuel Work Equivalents. The
natural work of nature includes winds to reduce air pollution,
waves to build and maintain beaches, tides, photosynthetic
productivity, etc., all of which contribute to the vitality
of a region. A region which is low in these energies will be
outcompeted by a region high in these energies if both systems
have the same economic mix, since the system with low natural
energies will have to subsidize work functions that would
otherwise be provided free. Thus, a higher ratio of total
work to fossil fuel work for a region will allow this region
to outcompete regions with a lower ratio.

Consider the diagram in Fig. 37 which shows the main
energy and money flows in a region, with selling price, P_2,
and external price, P_1. It can be seen that the larger
J_1+J_N/J_1 is, the smaller P_2 is compared to P_1, which means
that the region will sell at lower prices and outcompete
other regions that have a smaller ratio. Classical economics
leaves out the component of natural energy and arrives at the
condition that the ratio of flows should be inversely propor-
tional to the ratio of prices $(J_1/J_2 = P_2/P_1)$ in order to
maximize profits (Bishop and Toussaint, 1958).

Fig. 37. Diagram showing relationships of energy flows to prices. (From H. T. Odum and J. Zucchetto, unpublished paper.)
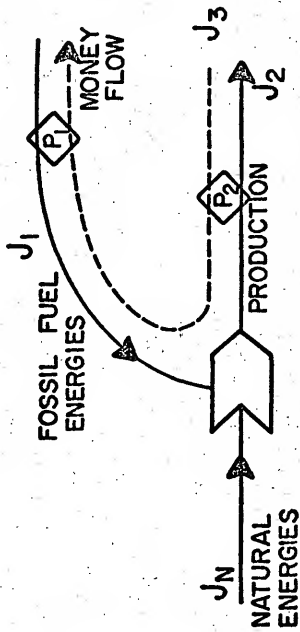
$J_1 = 73.6 \times 10^{12}$ kcal

$J_2 = 92.5 \times 10^{12}$ kcal

$J_3 = \$6.8 \times 10^9$

$J_N = 18.9 \times 10^{12}$ kcal

FOSSIL FUEL ENERGIES J_1

MONEY FLOW

P_1

P_2

PRODUCTION

J_3

J_2

J_N NATURAL ENERGIES

$J_2 = J_1 + J_N$

$J_3 = J_2 P_2 = J_1 P_1$

$P_2 = \dfrac{J_1}{J_2} P_1$

$P_2 = \dfrac{J_1}{J_1 + J_N} P_1$

Classical Economics Didn't Consider Natural Energies so that $J_N = 0$

$\dfrac{P_2}{P_1} = \dfrac{J_1}{J_2}$

and

For Dade County, then, the ratio is 1.25 as compared to 1.25 for Florida (Kylstra, 1974) and 1.4 for the region of South Florida (Fontaine and Brown, 1975). It would be expected that these neighboring regions will receive the bulk of new investment for they will outcompete Dade.

Future Outlook and Recommendations for Miami-Dade County

Population and Growth

As can be seen from the model simulation results, the system structure and population is limited. As discussed in previous paragraphs the factors interacting which result in limited growth are available energy, inflation, limited capital, maintenance costs of complex structure, and the destruction of natural system energies which are vital to the economic competitiveness of the region (see Fig. 37). Based on the tourist model in Fig. 27 the population curves in Fig. 28 show the population leveling at about 1.6 million with structure peaking about 1978. These results assume that 40% of the proven fossil fuel reserves in the United States are available for consumption (see note 1 to Table 7). Even for an increasing energy function as shown in Fig. 25a, the structure still peaks around 1980 but remains at a high level. This is due to the square drain maintenance costs of the system structure and increasing money expenditures for energy.

There are other considerations for predicting a leveling of the urban system as discussed in the paragraphs

accompanying Fig. 37 showing the natural energy contributions
to the competitiveness of a region. Those systems which have
a larger ratio of natural to fossil fuel energies will out-
compete systems with a smaller ratio because of the free work
services of nature. Under these criteria Dade County is over-
developed and therefore less competitive compared to other
regions in South Florida so that any new investment should be
attracted to regions other than Dade. This is a quantitative
way of saying that a hotel will more likely be put on a clean,
extensive beach than on an eroded and polluted one.

Agricultural Areas

Is it a prudent policy to develop the remaining agricul-
tural areas in Dade County as some developers would like to
do? As presented in the Energy-Economic Calculations section
the agricultural areas as they exist now could provide approx-
imately one-third of the carbohydrate and one-fourth of the
protein requirements of the Dade County population. This is
for the present food consumption of 3000 Kcal/person/day.
If fossil fuels become limiting at a national scale, then
putting the last energies into development while destroying
the contributions of agricultural energies could prove to be
disastrous. Putting energies into development would decrease
the natural to developed energy ratio and make the region
even less competitive as the price of services goes up. If
the United States is entering a depression in 1975, then the
availability of food-producing lands is a survival factor for
the county.

Another aspect to consider is the diversity of the
region. If the agricultural lands are developed, then the
county is headed for extensive urban sprawl, high cost of
services, congestion and decay that is characteristic of
practically every other urbanized region in the United States.
Leaving the agricultural sector maintains a diversity of labor
and land and provides a buffer during hard times. This is
especially true with regard to the shipment of food, for as
energy prices go up external food supplies will also increase
in price. Thus, a local supply of food will be economically
advantageous. There is also the question of how further
development will affect water quality and supply. If there
are extra funds and energy for growth perhaps these are more
wisely invested in redevelopment, maintenance, and adaptation
to a lower energy society.

Alternative Energy Sources

This dissertation has presented the fossil fuel and
natural energy contributions to the Dade County urban system.
There has been much speculation that other energy processes
can supply additional energy to human systems. Recycling of
garbage to produce additional fossil fuel energy has been
suggested but, as calculated in this dissertation, this would
only be a savings of about 2.7% of the total energy budget at
most and with possible hidden costs not considered.

Likewise, the use of solar energy to produce low grade
energy (heat) to perform such functions as heating water

would amount to a 3.5% savings in fuel if all electric water heaters were replaced over a period of 10 years, but there may be other greater energy effective uses of capital than for water heaters in a warm climate in a declining energy situation. Net energy calculations cast doubt on the question of whether solar energy technology could produce net energy in the form of electricity. Thus, the two methods discussed above for tapping some extra energy are at most small and not sufficient for running a high energy system. The recycling of materials from urban garbage can certainly provide a source of raw materials in short supply but it must be determined if it is energetically cheaper to recycle or produce these materials anew. Other sources of energy which may provide for further growth are Middle Eastern oil, coal, and nuclear energy if they provide net energy to the system of the United States. However, they will most likely have high costs associated with them.

The above discussion has concentrated on technological alternative energy sources. As the energy level of a society comes down, these diverse sources may be selected against. For example, less garbage will be produced and with it less potential for recycle. Similarly, useful work processes will probably outcompete hot water heaters for fuel use. However, the solar input to Dade County which drives the natural systems will still have a tourist multiplier effect, especially if these energies increase as fossil fuel energies decrease.

Energy Cost Benefit Considerations

It is recommended that any proposed changes or develop-
ments in the county be subjected to energy cost benefit cal-
culations (Odum, 1974) in order to determine whether a pro-
posed project will yield a higher energy value as compared to
other alternatives. This type of analysis will be especially
important as energy sources become limiting and natural ener-
gies must contribute vital energies for system survival.
This will be especially true if the water management of the
region is considered. The natural water system of the area
has been totally altered by man through the construction of
water management structures. This alteration of the natural
water system coupled with extensive urban development has
resulted in significant salt water encroachment, especially
during periods of drought. Methods have been proposed for
water conservation and recharge of the aquifer to prevent
salt water intrusion such as backpumping from the outlet of
the canals upstream to the conservation districts. How much
energy these plans will require plus the energy required to
maintain the water system functioning should be determined
for the future, especially in light of decreasing energy
supplies and increasing prices.

Many of the numbers presented and calculated in this
dissertation can be used in the study of future proposals in
Dade County. The Doxiadis Associates' (1967) master plan for
downtown Miami should be examined with consideration of avail-
able energy and costs for building this structure along with

that associated with the transportation technology which is necessary for providing access to this area. If this plan is anticipating future automobile growth and use based on past trends, then it must be rethought and revised as energy becomes more expensive.

Dade County Master Plan Approach

The Comprehensive Development Master Plan for Metropolitan Dade County prepared by the Metropolitan Dade County Planning Department (1973) is in many ways startling in that its tone and outlook is much different than studies previous to 1971. Most previous studies extrapolated existing growth into the future and thus predicted continued growth and development. Growth was good and the question was how to manage this growth. The General Land Use Master Plan had predicted a population of 2.5 million by 1985 but now the master plan is predicting somewhere between 1.6 and 1.8 million people. The tourist model in Fig. 27 predicted about 1.6 million people in 1985 (see Fig. 28c). Thus, the planners are beginning to respond to the reality of the energy situation as they monitor indicators such as tourism, migration, building growth, quality of life, carrying capacity, energy availability, and prices. If population modeling had been tied to energy sources in the sixties, perhaps the growth would have been seen to be limited.

It is also interesting that the Master Plan sets out such goals as:

a) A population ceiling should be determined.

b) Foster economic growth that will improve the standard of living both on an absolute and relative scale.

c) To achieve a harmonious relationship between man and his environment.

d) Recycle urban wastes.

e) Urban growth should be constrained by the carrying capacity of the Dade County environment.

f) Insure the preservation of beaches and wetlands.

g) Determine limitation on withdrawal from the Biscayne aquifer.

All of these goals point to the fact that more energies are going to be put into maintenance of the system and that consideration of the carrying capacity will result in logistic growth. In a sense this change in outlook of the planners is a validation of the model results presented in this dissertation. Further evidence for changes in the Miami urban system was a drop in tourism of about 30% for 1974 compared to 1972-73 and virtually no new construction permits with several large developments going bankrupt (Littlejohn, 1975). Construction is continuing on some developments which were already partially constructed.

Implications for Urban Living Patterns

There are many ways in which living styles and customs may change with adaptation to lower available energies and less urban structure. Less structure implies fewer automobiles, luxuries and buildings. People may migrate out of the

urban regions to rural areas. The pace of life will probably
slow down with less change, more stable communities, fewer
machines and more labor intensive jobs. Perhaps the business
district will decentralize to avoid the energy use of com-
muting and become dispersed throughout the urban region.
Communication will be maintained through telephones and tele-
visions. Extensive automobile use may be replaced by greater
use of buses, bicycles, and certainly more walking. Exten-
sive walking will provide much-needed exercise for large por-
tions of the population and increase the number of people on
the streets. This, coupled with the need for manual labor
and more stable communities, may help to decrease crime.

Even if some net energy is provided to the cities for
the next few decades, the establishment of a pleasing and
attractive human habitat will require channeling of energies
into maintenance of buildings, streets, parks and all services.
This may result in the achievement of an aesthetically pleas-
ing architecture with diversity of structure. Rather than
displacing old, stable communities with gigantic high-rise
buildings, these communities may be renovated with local
people serving as the labor force. The acquisition of mate-
rial things and planned obsolescence may be replaced by an
appreciation of a simple life style with mechanisms maintained
rather than replaced. There will be growth and change in some
areas of the economy and depression in others while, on the
average, the whole economy will maintain a nearly constant

level of activity. There will be change and development but at a slower pace.

Implementation for the Transition Period

The perennial problem of interfacing scientific and technical research and development to society is of special interest when considering the work in this dissertation. It seems as though the difficulty of introducing new ideas or innovations is directly related to the scale of the research since large-scale projects affect many people and groups. Resistance is greater. The research presented in this dissertation presents ideas and results which may affect and challenge existing values of the society.

Ideas can be circulated in the public arena through books, magazines, and educational institutions so that they will influence values and policies if they survive competition with other ideas. However, this process may take a long time so that federal, state, and local government can be looked to for implementing these ideas in the form of policies, laws, zoning, and taxation. Whether these governmental agencies have the power to make such changes in the face of powerful concentrations of energy and power (e.g., corporations) is an important question. Changes in policy can also be brought about through advocacy planning, consumer groups, and the courts.

As the energy level of society shifts the distribution of energy, and therefore of money and political power, will

shift and redistribute. The key question is how this politi-
cal power will be redistributed. In Dade County lower energy
levels may shift power to agricultural areas and diminish
manufacturing growth and power. Tourism will probably still
exist as an important source of income but greatly diminished.
In Florida, the counties control development through zoning
and permits. The county agencies are, in turn, heavily influ-
enced by local economic interests.

Other Urban Patterns

Whereas the Miami urban region, like other American
urban systems, has been a fast-growing, successional system
characterized by a high ratio of net growth to recycle, other
cities have energy constraints which require recycle of mate-
rials and a low ratio of net growth to recycle. As an example
of a recycle model, the following paragraphs describe an
order-disorder model for the urbanization of South Vietnam.

Urbanization Model for South Vietnam*

Perhaps the most striking example of the disordering
process in the rapid development of an urbanized society has
occurred in South Vietnam during the war years 1963-72. As
in other under-industrialized countries, the rapid transfor-
mation from an agrarian to an urbanized society has resulted
in various kinds of disruptions and disorderings in the social
and physical systems. The intense conflict between United
States military forces and Communist forces resulted in

*Sponsored by National Research Council Subcontract
BA 23-72-28.

widespread destruction due to combat troops, intense bombing,
and widespread herbiciding. American aid in the form of fuel
and material which, along with the natural system energies,
operate on the destruction to maintain and develop the agri-
cultural and urban sectors. Figure 38 presents a macro-model
of the processes taking place in Vietnam. The ecosystem and
agricultural system are destroyed by herbicides for a period
of five years, along with other forms of war destruction for
15 years. The natural ecosystem also loses by being developed
and converted into agricultural and urban land through an
interaction with fuels and disordered parts. Disordered
parts are created from the natural, agricultural and urban
compartments by virtue of the war and normal deterioration.
This represents an order-disorder cycle. The rates of devel-
opment were estimated from 1965-66 data and are summarized in
Table 18. Unknown flows such as the natural deterioration or
depreciation rate were approximated to be 2% per year, which
is a conservative figure. The equations representing the
model are on the legend to Fig. 38.

    Figure 39a shows the result of a simulation run with a
5-year herbicide pulse and a 15-year war pulse with a recycle
of disordered parts to the natural ecosystem. Perturbations
are produced during the initial 10-15 years but the system
has enough stability as a result of input of natural and
fossil fuel energies to quickly recover and achieve a steady-
state. The results in Fig. 39b come about if it is assumed
that there is no recovery of disordered lands to natural

Fig. 38. Urbanization model for the country of South Vietnam showing major sectors including natural ecosystems, agricultural systems, and urban systems. There is a recycle pathway of destroyed areas through a storage of disordered parts. Equations describing the model are:

$$\dot{Q}_1 = S + K_0 Q_2 - K_3 Q_1 CW - K_1 Q_1 - K_{31} Q_1 H - K_2 Q_1 Q_2 M$$

$$\dot{Q}_2 = K_4 M + K_5 CW (Q_1 + Q_4) + K_{21} H (Q_1 + Q_3) - K_6 Q_1 Q_2 M$$

$$\dot{Q}_3 = K_7 Q_1 Q_2 M - K_8 Q_3 CW - K_9 Q_3 - K_{30} Q_3 H$$

$$\dot{Q}_4 = K_{11} Q_1 Q_2 M - K_{12} Q_4 - K_{13} Q_4 CW$$

$$\dot{M} = K_4 Q_3 + A - K_{15} M - K_{16} M + W$$

Table 18

Storages and Flows for South Vietnam Model

Mathematical Quantity	Note[a]	Description	Numerical Values	Reference
Q_1	1	Ecosystem Lands (Upland Forest and Mangrove)	19.19×10^6 acres	Vietnam Statistical Yearbook, 1970
Q_2	2	Disordered Parts (Forest, Agriculture and City)	25×10^4 acres	U.S. Congress House Committee on Appropriations, 1970
Q_3	3	Agricultural Land	7.31×10^4 acres	
Q_4	4	Urban Land	2.47×10^4 acres	Odum, Sell, et al., 1974
M	5	Capital in City	$281 million	
H	6	Herbicide Use	644×10^3 gal/yr	
C	7	Communist Energies	$555 million/yr	
$K_{11}Q_1Q_2M$	8	Rate of Growth of Urban Land	1235 acres/yr	
$K_7Q_1Q_2M$	9	Bare Forest Land Returning to Agriculture	5600 acres/yr	
K_8Q_3CW	10	Replanted Agricultural Land	4.5×10^4 acres/yr	
K_3Q_1CW	11	Ecosystem Land Destroyed	7.95×10^3 acres/yr	
W	12	U.S. War Appropriations	$200 million/yr	

Table 18 - Continued

Mathematical Quantity	Note[a]	Description	Numerical Value	Reference
A	13	U.S. Aid	$250 million/yr	
K_4M	14	Purchased Input	$50.3 million/yr	
$K_5CW(Q_1+Q_3+Q_4)$	15	Structure Destroyed	40×10^3 acres/yr	
$K_{14}Q_3$	16	Money in Due to Sales	$40.5 million/yr	
$(K_{15}+K_{16})M$	17	Money to Purchase Goods and Fuels	$130.5 million/yr	
$K_{16}M$	17	Money to Purchase Fuels	$80.5 million/yr	
$K_6Q_1Q_2M$	18	Bare Land Returning to Agriculture	14500 acres/yr	
$K_{11}Q_1Q_2M$	19	Natural Land → Urban Land	1235 acres/yr	
$K_7Q_1Q_2M$	20	Natural Land → Agricultural Land	5600 acres/yr	
K_8Q_3CW	21	Rural Destruction	4.5×10^4 acres/yr	
K_0Q_2	22	Rate of Return of Disordered Land to Natural Land	1.25×10^4 acres/yr	
$K_{31}Q_1H$	23	Ecosystem Herbicide Destruction	1.5×10^5 acres/yr	
$K_{30}Q_3H$	24	Agricultural Herbicide Destruction	5.94×10^4 acres/yr	

Table 18 - Continued

Mathematical Quantity	Note[a]	Description	Numerical Values	Reference
$K_{21}H(Q_1+Q_3+Q_4)$	25	Total Herbicide Destruction	21×10^4 acres/yr	
$K_{13}Q_4^{CW}$	26	Urban Bomb Destruction	890 acres/yr	
$K_2Q_1Q_2^M$	27	Total Ecosystem Transformation Into Rural and Urban	6835 acres/yr	
K_9Q_3	28	Depreciation	$.02\ Q_3$/yr	
$K_{12}Q_4$	28	Depreciation	$.02\ Q_4$/yr	

[a]Notes are contained in Appendix II.

Fig. 39. Simulation results for Vietnam model.

        a.   Simulation results for model in Fig. 38
            with recovery of natural lands
            $(k_0 Q_2 \neq 0)$.

        b.   Simulation results for model in Fig. 38
            with no recovery of natural lands
            $(k_0 Q_2 = 0)$.
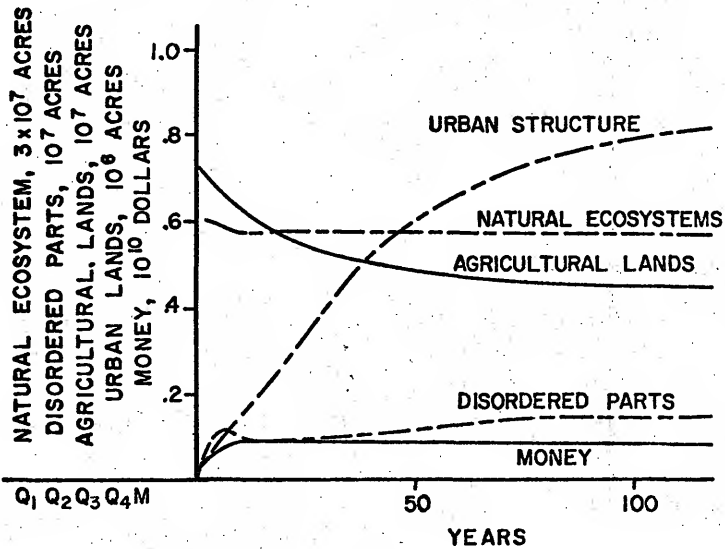
(a.)
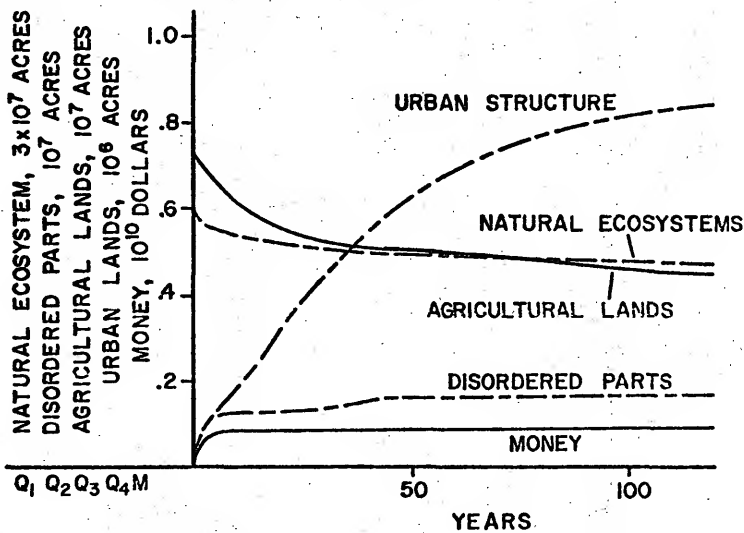
(b.)

Fig. 40.   Simulation results for model in Fig. 38
           showing urban sector as a function of
           three different levels of U.S. aid.
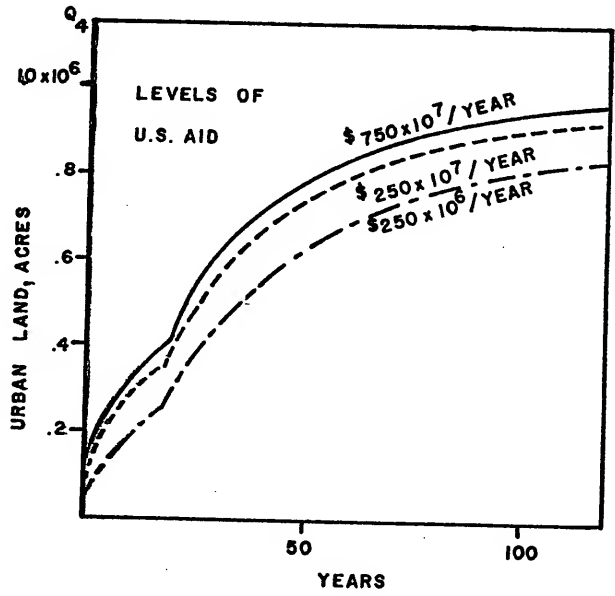
ecosystems $(k_0 Q_2)$. This might come about if a political
decision is made to develop the devastated natural areas.
Ecosystem lands end up at a value approximately 16% lower
than in Fig. 39a. It is interesting to note that in all the
graphs urban development follows a kind of pseudo-logistic
curve even though there is only a linear depreciation outflow
and a constant yearly rate of energy input. Since U.S. aid
is one of the primary ordering energies the response of the
system to different levels of aid is of interest. Figure 40
presents urban growth for three different levels of U.S. aid
which shows there is not a linear correspondence between U.S.
aid and growth. This may indicate a process of diminishing
returns in that the percentage increase in growth is decreas-
ing with equal increments of U.S. aid.

Examination of the simulation curves suggests magnitudes
of impact of the herbicide spraying period on the total
energy flow of the Vietnam system. As shown in Fig. 39a, the
percentage of energy lost, as a fraction of the area under
the disordered parts curve until steady-state is reached, is
approximately 5-6%. The impact of herbicides exerts a short-
range effect, damping out within a period of 5 years, as long
as foreign aid is stimulating reordering.

Summary

In summary, then, this dissertation dealt with aspects
of the urban system in terms of an energetic formulation.
Although the theory presented here could be used for any urban
region, the area of Dade County was used as a study area
since it is extensively urbanized and one for which data were
available. Time series data from 1950 to 1972 were collected
for many urban parameters and the rates of change of these
variables correlated well with the rates of change for fossil
fuel energy use. Based on the data and energy concepts, a
set of urban indicators were calculated which could be used
when making comparisons to other urban systems. Borrowing
from ecosystem modeling, a detailed model of Miami and Dade
County was constructed (Fig. 19) to show values of flows
including natural energies. Based on this model several
simplified models were constructed and analog computer simu-
lated to show the effects of available energy and price on
the growth of the system. These models included two general-
ized models (Figs. 20 and 24) and a tourist model (Fig. 27)
which were subjected to different functions of available
energy and price. The results show that the higher the rate
of increase in price, the sooner and lower the urban struc-
ture peaks. Different price functions also affect fossil
fuel reserves, fuel expenditures, and money storage differ-
ently. Higher prices inhibit the use of fossil fuels and
decrease the money available for purchasing. Changes in the

energy input function to the urban system also resulted in different responses. The tourist model indicated the effect of changes in tourist dollars on urban and natural parts of the system. If there are not any sudden discoveries of available energy in the country, Dade County structure should peak in the next few years and level with the population perhaps reaching 1.6 million in the next ten years. This population increase may be offset if there are migrations back to rural areas. If new net energy sources are developed, then growth will continue and peak at a later date and a higher level.

Calculations were made for the major economic and energy flows in the system, especially the major sources of fossil fuel and those associated with the natural areas in the county. In order to calculate these natural system energies, subsystems in the county were identified, their areas measured, and a land use map was constructed. A table of energy flows was also constructed.

In order to compare natural system and fossil fuel energies the concept of energy quality was employed, which allows theoretical assessment of the ability of energy flows with different energy concentrations to do useful work. The ratio of total energy flow to fossil fuel flow changed from 2.77 in 1950 to 1.25 in 1972, compared to a value of 1.4 in 1972 for the region of South Florida. An estimate of the energy recoverable from garbage in Dade County, assuming that the level of the system remains the same, was calculated as 2.08×10^{12} Kcal/yr, which represents 2.7% of the 1972 fossil

fuel consumption. It was also estimated that the agricul-
tural lands in the county could provide one-third of the
carbohydrate and one-fourth of the protein requirements of
the population for existing levels of population and con-
sumption. Several energy to money ratios were also calcu-
lated.

An analysis of solar energy technology applied to water
heating was also conducted, with results showing that a solar
system would save both money and energy over an electrical
system. This was not true when compared to a natural gas
water heater. The question still remains, however, whether
capital and energy should be invested in a luxury such as
water heating rather than a more survival-related activity.
This technology applied to water heating would have saved
3.5% of the total energy consumed in 1972. The results pre-
sented in this dissertation for the future of Dade County
seem to agree with the new outlook and predictions of the
Dade County Planning Department, which sees much smaller
growth than previously predicted along with a consideration
of logistic growth effects. Their population predictions are
similar to those presented in this dissertation.

Finally, an order-disorder urbanization model was con-
structed for the country of South Vietnam to show the effects
of foreign aid, energy, and war on the development of an
entire country. The model shows diminishing returns on
foreign aid invested in the country. This system between
order and recycling parts and lands is a future of cities and
countries as well as of forests and seas.

APPENDIX I

TABLES OF DATA FOR FLORIDA AND DADE COUNTY

Table 19

Energy Data for Florida Not Including Electrical Utilities[1]

Year	Natural Gas, 10^6 Ft.^{3}	Liquid Petroleum Fuel, 10^6 Barrels	Distillate, Residual and Kerosene Fuel, 10^6 Barrels	Population, 10^6 People
1950	8346	1.481	10.59	2.81
51	7789	1.605	12.45	2.967
52	9202	1.873	15.09	3.118
53	10656	2.187	16.25	3.284
54	14783	2.652	22.334	3.462
55	18467	3.139	28.432	3.67
56	23529	3.589	27.795	3.941
57	27670	3.655	27.453	4.245
58	33960	4.73	25.678	4.57
59	40945	4.76	28.245	4.79
1960	49357	4.935	28.183	4.999
61	59129	4.936	26.75	5.205
62	68716	5.405	27.16	5.392
63	81953	6.001	28.7	5.541
64	92855	6.373	29.0	5.781
65	101389	5.67	30.6	5.954
66	114588	6.095	31.4	6.104
67	117716	6.22		6.242
68	127968	6.344		6.433
69	126838	7.32	26.9	6.641
1970	133886	7.837	32.2	6.845
71	136698	7.539	30.84	7.041
72	122957	7.871	30.56	7.495

NOTE: Note 1 is contained in Appendix II.

Table 20

Dade County Data for Selected Urban Indicators[2-7]

Year	Budget, $10^6	Building Permits, 10^6/yr	Building Structure Growth, 10^6 ft2/yr	Building Structure (Total) Above 1949 Level,[3] 10^6 ft2	Distillate, Kerosene & Fuel,[4] 10^6 Barrels	Residual Fuel,[4] 10^{12} Kcal	Effective Buying Income $10^9
1950	14.65	194.58	46	46	1.86	3.01	
51	20.13	161.68	37	83	2.26	3.66	
52	22.32	174.53	38	121	2.78	4.50	
53	25.41	204.99	44	165	3.07	4.97	
54	24.79	226.49	47	212	4.29	6.95	
55	28.59	256.2	52	264	5.49	8.89	
56	30.65	273.15	54	318	5.36	8.68	
57	38.94	303.3	58	376	5.29	8.57	
58	45.24	266.29	50	426	4.88	7.90	
59	54.41	282.09	51	477	5.30	8.58	
1960	59.89	241.93	43	520	5.27	8.53	
61	59.43	227.97	39	559	5.016	8.12	
62	62.66	225.33	38	597	5.198	8.42	
63	65.11	200.6	33	630	5.516	8.93	2.315
64	65.79	239.72	39	669	5.417	8.77	2.554
65	71.00	290.53	44	713	5.637	9.13	2.715
66	76.27	274.99	41	754	5.778	9.36	2.78
67	88.87	334.58	48	802			2.962
68	102.79	479.09	67	869			3.351
69	116.03	691.96	87	956	4.96	8.03	3.77
1970	128.07	613.19	72	1028	5.96	9.65	4.435
71	149.87	760.0	83	1110	5.761	9.33	4.809
72	172.65	1300.0	150(?)		5.576	9.03	5(?)

NOTE: Notes 2-7 are contained in Appendix II.

Table 20 - Continued

Year	Electrical Energy, 10^9 Kwh	Electrical Energy, 10^12 Kcal	Gasoline Energy, 10^8 gal	Gasoline Energy, 10^12 Kcal	Electrical & Gasoline Energy, 10^12 Kcal	Labor Force, 10^3 people	Liquid Petroleum, 10^6 Barrels	Liquid Petroleum, 10^12 Kcal
1950	0.78	2.68	1.42	5.11	7.79		0.26	0.264
51	0.943	3.24	1.53	5.51	8.75		0.29	0.294
52	1.099	3.78	1.70	6.12	9.9		0.345	0.35
53	1.283	4.42	1.86	6.7	11.12		0.413	0.419
54	1.464	5.04	2.04	7.35	12.39		0.51	0.518
55	1.714	5.92	2.25	8.1	14.02		0.61	0.62
56	1.994	6.88	2.53	9.1	15.98		0.69	0.70
57	2.319	8.00	2.72	9.8	17.8		0.71	0.72
58	2.666	9.16	2.79	10.05	19.21		0.9	0.91
59	3.002	10.32	2.89	10.4	20.72		0.89	0.90
1960	3.344	11.52	2.91	10.48	22.0		0.92	0.934
61	3.62	12.48	2.98	10.72	23.2		0.926	0.94
62	3.959	13.64	3.22	11.6	25.24		1.035	1.05
63	4.357	15.0	3.33	11.98	26.98	426.4	1.153	1.17
64	4.763	16.4	3.51	12.63	29.0	434.8	1.19	1.21
65	5.121	17.6	3.61	13.0	30.6	458.5	1.044	1.06
66	5.676	19.52	3.80	13.68	33.2	478.2	1.121	1.14
67	6.295	21.6	4.13	14.88	36.48	519.8		1.16
68	7.154	24.64	4.47	16.1	40.74	545.5	1.173	1.19
69	8.166	28.08	4.84	17.4	45.48	586.3	1.35	1.4
1970	9.134	31.4	5.23	18.82	50.22	608.2	1.45	1.47
71	10.118	35.0	5.59	20.1	55.1	631.6	1.408	1.43
72	11.238	38.68	6.04	21.75	60.43	643.3	1.44	1.46

Table 20 - Continued

Year	Natural Gas 10^6 ft3	10^12 Kcal	Net Migration, 10^3 people/yr	Population (Total) 10^6 people	Retail Sales, $10^9	Sales Tax Collections, $10^6	Telephones (Total), 10^3 units
1950	652.2	0.177		0.495		12.76	200.68
51	628.1	0.171	37.0	0.5388		14.78	221.25
52	751.7	0.204	28.5	0.5476		16.28	245.29
53	894.1	0.243	39.0	0.6215		18.52	267.63
54	1260.3	0.343	35.0	0.6653		19.52	297.17
55	1582.5	0.43	35.5	0.7098		22.62	325.85
56	2016.3	0.548	41.5	0.7613		26.37	371.72
57	2371.0	0.645	48.0	0.8204		32.64	419.93
58	2864.8	0.779	37.0	0.8686	1.366	36.31	450.39
59	3417.8	0.93	22.5	0.9025	1.509	39.79	488.16
1960	4097.9	1.115	21.5	0.935		41.67	516.72
61	4922.4	1.34	29.5	0.9758		40.37	546.82
62	5839.5	1.59	46.0	1.0322		43.01	556.97
63	6993.7	1.90	22.5	1.065	1.58	44.44	595.53
64	7701.4	2.09	6.0	1.08	1.797	53.1	615.1
65	8292.0	2.26	9.0	1.097	2.035	58.94	649.46
66	9361.4	2.55	20.0	1.1237	2.214	63.7	689.94
67	9679.7	2.63	26.0	1.1558	2.413	69.8	740.54
68	10505.6	2.86	28.5	1.1896	2.61	99.7	792.65
69	10390.3	2.83	30.5	1.2255	2.614	129.24	859.68
1970	11009.3	2.99	37.0	1.267	2.62	140.23	918.13
71	11337.5	3.08	41.0	1.3154	2.82	155.0	995.5
72	9974.3	2.71	46.5	1.3676	3(?)	178.57	1093.0

Table 20 - Continued

Year	Total Fossil Fuel Energy, 10¹² Kcal	Tourist Flow, 10⁶/yr	Vehicles, (Total), 10³ units	Water Consumption, 10⁹ gal
1950	11.241		222.84	18.08
51	12.875		247.18	19.69
52	14.954		262.6	22.29
53	16.752		292.48	21.52
54	20.201		322.82	23.01
55	23.96		377.09	26.07
56	25.908	2.56	405.36	26.57
57	27.735	2.856	448.74	29.29
58	28.8	2.248	457.31	29.16
59	31.13	4.0	480.51	31.59
1960	32.58	3.95	493.0	32.44
61	33.6	4.4	502.08	35.33
62	36.3	4.6	529.17	38.25
63	38.98	5.0	550.9	39.64
64	41.1	5.2	556.0	45.16
65	43.05	5.5	603.35	51.31
66	46.25	6.0	633.4	45.96
67	49.28	6.6	671.21	48.6
68	53.79	7.2	730.92	50.13
69	57.74	7.5	796.46	50.04
1970	64.33	10.0	823.44	55.88
71	68.94			58.07
72	73.63			59.56

Table 21

Dade County Per Capita Data for Selected Urban Variables[8]

Year	Budget, Dollars	Building Permits, Dollars	Building Structure Growth ft2/yr	Building Structure (Total) Above 1949 Level, ft2	Distillate, & Kerosene Barrels	Residual Fuel, 106 Kcal	Effective Buying Income, $103
1950	29.6	393.1	92.9	93.0	3.76	6.08	
51	37.4	300.0	68.7	154.0	4.19	6.79	
52	40.8	318.7	69.4	221.0	4.84	7.83	
53	40.9	329.8	70.8	265.0	4.94	7.80	
54	37.3	340.4	70.6	318.0	6.45	10.45	
55	40.3	360.9	73.3	372.0	7.73	12.52	
56	40.3	358.8	70.9	418.0	7.04	11.40	
57	47.5	369.7	70.7	458.0	6.45	10.45	
58	52.1	306.6	57.6	490.0	5.62	9.10	
59	60.3	312.6	56.5	529.0	5.87	9.51	
1960	64.0	263.31	46.0	556.0	5.64	9.12	
61	60.9	238.61	40.0	573.0	5.14	8.32	
62	60.7	224.43	36.8	578.0	5.04	8.16	
63	61.1	191.23	31.0	592.0	5.18	8.38	
64	60.9	223.62	36.1	619.0	5.02	8.12	2.207
65	64.7	266.79	40.1	650.0	5.14	8.32	2.382
66	67.9	247.74	36.5	671.0	5.14	8.33	2.493
67	76.9	293.49	41.5	694.0		7.79	2.505
68	86.4	408.43	56.3	730.0		7.57	2.598
69	94.7	572.8	71.0	780.0	4.05	6.55	2.857
1970	101.0	491.73	56.8	811.0	4.70	7.61	3.121
71	113.9	588.24	63.0	844.0	4.38	7.09	3.557
72	126.2	968.7			4.08	6.60	3.722

NOTE: Note 8 is contained in Appendix II.

Table 21 - Continued

Year	Electrical Energy, 10^3 Kwh	Electrical Energy, 10^6 Kcal	Gasoline Gallons	Gasoline Energy, 10^6 Kcal	Labor Force	Liquid Petroleum, Barrels	Liquid Petroleum, 10^6 Kcal	Natural Gas, ft^3	Natural Gas, 10^6 Kcal
1950	1.58	5.41	281.0	10.30		0.53	0.533	1318	0.358
51	1.75	6.01	264.0	10.23		0.54	0.546	1166	0.317
52	1.91	6.58	294.0	11.18		0.60	0.609	1308	0.355
53	2.06	7.11	304.0	10.58		0.66	0.674	1439	0.391
54	2.20	7.58	313.0	10.83		0.77	0.779	1894	0.516
55	2.41	8.34	327.0	11.25		0.86	0.873	2230	0.606
56	2.62	9.04	326.0	11.78		0.91	0.919	2648	0.720
57	2.83	9.75	317.0	11.73		0.87	0.878	2890	0.786
58	3.07	10.55	317.0	11.41		1.04	1.048	3298	0.897
59	3.33	11.43	309.0	11.41		0.99	1.0	3787	1.03
1960	3.58	12.32	302.0	11.12		0.98	0.99	4383	1.19
61	3.71	12.79	309.0	10.88		0.95	0.96	5044	1.37
62	3.84	13.20	313.0	11.12		1.00	1.02	5657	1.54
63	4.15	14.08	326.0	11.25	0.40	1.08	1.1	6567	1.78
64	4.44	15.19	330.0	11.73	0.40	1.10	1.12	7131	1.94
65	4.70	14.95	339.0	11.88	0.42	0.95	0.966	7557	2.06
66	5.11	17.37	358.0	12.20	0.43	1.00	1.015	8331	2.27
67	5.52	18.69	377.0	12.90	0.45		1.004	8375	2.28
68	6.10	20.70	396.0	13.58	0.46	0.99	1.0	8831	2.40
69	6.76	22.90	412.0	14.25	0.48	1.10	1.14	8478	2.31
1970	7.32	24.77	425.0	14.83	0.48	1.14	1.16	8684	2.36
71	7.83	26.60	441.0	15.30	0.48	1.07	1.09	8619	2.34
72	8.37	28.28		15.90	0.47	1.05	1.07	7293	1.98

Table 21 - Continued

Year	Retail Sales, 10^3	Sales Tax Collections, Dollars	Telephones	Total Fossil Fuel Energy, 10^6 Kcal	Vehicles	Water Consumption, 10^3 Gallons
1950		25.77	0.405	22.7	0.45	36.52
51		27.43	0.411	23.9	0.46	36.54
52		28.33	0.427	26.03	0.48	38.8
53		29.8	0.431	26.95	0.47	34.6
54		29.34	0.447	30.36	0.49	34.59
55		31.87	0.459	33.76	0.53	36.73
56		34.64	0.488	34.03	0.53	34.9
57		39.79	0.512	33.81	0.55	35.7
58	1.573	41.8	0.519	33.16	0.53	33.57
59	1.67	44.09	0.541	34.5	0.53	35.0
1960		44.56	0.553	34.84	0.53	34.7
61		41.37	0.56	34.4	0.51	36.2
62		41.67	0.54	35.17	0.51	37.06
63	1.506	42.36	0.568	36.6	0.52	37.79
64	1.676	49.53	0.574	38.06	0.51	42.13
65	1.869	54.12	0.596	37.46	0.55	47.12
66	1.995	57.39	0.622	38.3	0.56	41.41
67	2.117	61.23	0.65	42.64	0.58	42.63
68	2.225	85.0	0.676	45.22	0.61	42.74
69	2.164	106.99	0.712	47.12	0.65	41.42
1970	2.10	112.45	0.736	50.74	0.65	44.81
71	2.183	119.97	0.771	52.41		44.95
72	2.26(?)	133.06	0.814	53.84		44.38

Table 22A

Rate of Change per Year for
Selected Urban Variables in Dade County

Year Interval	Budget, 10^6	Budget per Capita, Dollars	Effective Buying Income, 10^9	Electrical Energy, 10^{12} Kcal	Gasoline Energy, 10^{12} Kcal	Labor Force, 10^3 People	Population, 10^6 People
1950-51	5.48			0.56	0.4		0.0438
51-52	2.19	1.15		0.54	0.612		0.0398
52-53	3.09	2.4		0.63	0.576		0.0413
53-54	-0.62	-3.96		0.62	0.648		0.0454
54-55	3.8	3.06		0.88	0.756		0.0441
55-56	2.06	0.08		0.96	1.01		0.0481
56-57	8.29	7.57		1.12	0.684		0.0553
57-58	6.3	4.33		1.16	0.252		0.0536
58-59	9.17	7.88		1.16	0.36		0.041
59-60	5.48	3.73		1.2	0.072		0.033
1960-61	-0.46	-2.98		0.96	0.252		0.0366
61-62	3.23	0.21		1.16	0.865		0.0486
62-63	2.45	-0.34		1.36	0.396		0.045
63-64	0.68	-0.7	0.239	1.4	0.648	8.4	0.023
64-65	5.21	3.83	0.161	1.23	0.37	23.7	0.017
65-66	5.27	3.51	0.065	1.9	0.684	19.7	0.021
66-67	12.6	9.25	0.182	2.13	1.198	41.6	0.03
67-68	13.92	9.67	0.389	2.95	1.222	25.7	0.033
68-69	13.24	8.42	0.419	3.48	1.33	40.8	0.035
69-70	12.04	6.65	0.665	3.33	1.402	21.9	0.039
1970-71	21.8	13.3	0.374	3.38	1.295	23.4	0.045
71-72	22.78	12.7	0.39(?)	3.85	1.62	11.7	0.05

Table 22B

Rate of Change or First Differences
for Selected Urban Variables[9]

Year Interval	Retail Sales, 10^9	Sales Tax Collections, 10^6	Telephones, 10^3 Units	Total Fossil Fuel Energy, 10^{12} Kcal	Water Consumption, 10^9 Gallons
1950-51		2.02	20.57	1.63	1.61
51-52		1.5	24.04	2.08	2.6
52-53		2.24	22.34	1.8	-0.77
53-54		1.0	29.54	3.5	1.49
54-55		3.1	28.68	3.76	3.06
55-56		3.75	45.87	1.95	0.5
56-57		6.27	48.21	1.83	2.72
57-58	0.143	3.67	30.46	1.07	-0.13
58-59		3.48	37.77	2.33	2.43
59-60		1.88	28.56	1.45	0.85
1960-61		-1.3	30.1	1.02	2.89
61-62		2.64	10.15	2.7	2.92
62-63		1.43	38.56	2.68	1.39
63-64	0.217	8.66	19.6	2.12	5.52
64-65	0.238	5.84	34.4	1.95	6.15
65-66	0.179	4.76	40.4	3.2	-5.35
66-67	0.199	6.1	50.6	3.03	2.64
67-68	0.197	29.9	52.2	4.51	1.53
68-69	0.004	29.54	67.0	3.95	-0.09
69-70	0.006	10.99	58.4	6.6	5.84
1970-71	0.20	14.77	77.4	4.6	2.19
71-72	0.10	23.57	97.5	4.7	1.49

NOTE: Note 9 is contained in Appendix II.

APPENDIX II

NOTES TO TABLES 6, 7, 8, 11, 13,
14, 18, 19, 20, 21, and 22

Notes to Table 6

1. Approximately 10^{12} gallons/yr recharges aquifer (Windham).

2. Sunlight energy falling on Dade County approximately equal to

$$\text{sunlight} = 4000 \text{ Kcal/m}^2/\text{day} \times 365 \text{ days/yr}$$
$$\times 1924 \text{ mile}^2 \times \frac{2.59 \times 10^6 \text{ m}^2}{\text{mile}^2}$$
$$= 73.6 \times 10^{14} \text{ Kcal/yr}$$

3. See note 17 to Table 11.

4. It was assumed that the average intake/person is 3000 Kcal/day which is

$$3000 \text{ Kcal/capita /day} \times 1.37 \times 10^6 \text{ people} \times \frac{365 \text{ days}}{\text{yr}}$$
$$= 15 \times 10^{11} = 1.5 \times 10^{12} \text{ Kcal/yr}$$

5. Based on percentage increase in no. of vehicles from 1969-70 which was approximately 3.4%. This comes out to be 29,000 vehicles/yr for 1972-73 if number of vehicles in 1971 is multiplied by .034:

.034 x 851,000 = 29,000.

6. Transfer payments = $.57 x 10^9 for 1970. Property income = $.73 x 10^9 for 1970. Assume values for 1972 are those of 1970 corrected by the ratio of 1972 to 1970 population:

$$\frac{\text{Population (1972)}}{\text{Population (1970)}} = \frac{1.368}{1.267} = 1.079$$

Transfer payments (1972) = $.57x(1.079)B = $.62 Billion

Property income (1972) = $.73x(1.079)B = $.79 Billion

Total =$1.41 Billion

7. Major Federal subsidies include:

    1) Dept. of Commerce = $6 x 10^6
    2) H.E.W. = $334 x 10^6
    3) Dept. of Housing & Urban Development = $30.4 x 10^6
    4) Dept. of the Interior = $3.4 x 10^6
    5) Dept. of Justice = $5.2 x 10^6
    6) Dept. of Labor = $8.3 x 10^6
    7) General Services Admin. = $4 x 10^6
    8) Post Office Dept. = $47.1 x 10^6
    9) All other except transportation = $355 x 10^6

$$\text{Total} = \$793 \times 10^6$$

Multiply by ratio of 1972 to 1970 population to get $856 x 10^6.

8. Taken as a total income minus effective buying income for 1970. Taxes = $5.7 x 10^9 minus $4.44 x 10^9 = $1.26 x 10^9. For 1972 multiply by ratio of 1972/1970 population to get $1.36 x 10^9.

9. The sum of hydrocarbons, CO, NO_2, SO_2, NO_3, particulates, aldehydes, organic acids and other organics amounts to 915,453 tons for 1970.

10. The amount of developed land was 260 square miles in 1972 and 202 square miles in 1960 (see Table 5). The average rate of development is

$$\frac{260-202 \text{ miles}^2}{12 \text{ years}} = 4.8 \text{ miles}^2/\text{year}$$

11. Money spent in 1967 for vehicles was $2.099 x 10^9 (Fla. Statistical Abstract, 1973). Ratio of vehicles in 1972 to that in 1967 was approximately 1.31. Therefore, assume money spent for vehicles in 1972 was approximately $2.0 x 10^9 x 1.31 = $2.6 x 10^9.

12. Approximately 25% of family budget is used to buy food (Fla. Statistical Abstract, 1973). Total effective buying income of Dade County for 1972 was approximately 5×10^9 so that money spent for food was approximately 1.25×10^9.

13. Energy flow is the sum of electrical energy, gasoline, natural gas, distillate, residual and kerosene. Fossil fuel equivalent of electrical energy = 4 x (kwh used) because conversion of fuel into electrical energy requires an energy ratio of 4:1 (see Table 1). Thus,

Electrical energy = $4 \times 9.67 \times 10^{12}$ Kcal = 38.68×10^{12} Kcal

Gasoline energy = 6.04×10^8 gal x 3.6×10^4 Kcal/gal
$$= 21.75 \times 10^{12} \text{ Kcal}$$

Natural gas = 2.71×10^{12} Kcal

Distillate + Residual + Kerosene = 8.07×10^{12} Kcal

Total $\approx 73.63 \times 10^{12}$ Kcal.

14. Average price of fuel calculated to be $.804 \times 10^{-3}$ cents/Kcal (see note 15 below).

Total money = $.804 \times 10^{-3}$ cents/Kcal x 73.63×10^{12} Kcal

Total money = 59.2×10^7 dollars

15. 1971-72 prices of fuels were (Minerals Yearbook, Fla. Statistical Abstract, 1973):

Natural gas: $1.39/10^3$ ft^3

or $.003676$ ft^3/Kcal x $1.39/10^3$ ft = $.51 \times 10^{-5}$/Kcal

Distillate fuel: 11.9¢/gallon

or 11.9¢/gal x $\frac{42 \text{ gal}}{\text{barrel}}$ x $\frac{1 \text{ barrel}}{1.6192 \times 10^6 \text{ Kcal}}$
$$= \$.31 \times 10^{-5}/\text{Kcal}$$

Residual fuel: $4.51/barrel

or $4.51/\text{barrel} \times \dfrac{1 \text{ barrel}}{1.6192 \times 10^6 \text{ Kcal}} = \$.28 \times 10^{-5}/\text{Kcal}$

LP gas: 11.6¢/gal

or $\dfrac{11.6¢}{\text{gal}} \times \dfrac{42 \text{ gal}}{\text{barrel}} \times \dfrac{1 \text{ barrel}}{1.6192 \times 10^6 \text{ Kcal}} = \$.3 \times 10^{-5}/\text{Kcal}$

Gasoline: 40¢/gal

or $\dfrac{40¢}{\text{gal}} \times \dfrac{1 \text{ gal}}{3.6 \times 10^4 \text{ Kcal}} = \$1.1 \times 10^{-5}/\text{Kcal}$

Electricity: 2.6¢/kwh

or $2.6¢/\text{kwh} = \dfrac{1 \text{ kwh}}{859.85 \text{ Kcal}} = \$3.02 \times 10^{-5}/\text{Kcal}$ (of high quality energy)

$$= \$3.02/4 \times 10^{-5}/\text{Kcal}$$

$$= \$.76 \times 10^{-5}/\text{Kcal of fossil fuel energy}$$
used to generate electricity

The average price for all fuel is a weighted average of the above prices:

Average price $= \$.51 \times 10^{-5} \dfrac{2.71}{73.63} + \dfrac{\$(.31+.28)}{2}$

$\times 10^{-5} \dfrac{9.03}{73.63} + \$.3 \times 10^{-5} \dfrac{1.46}{73.63} + \$1.1$

$\times 10^{-5} \dfrac{21.75}{73.63} + \$.76 \times 10^{-5} \dfrac{38.68}{73.63}$

Average price $= \$.804 \times 10^{-5}/\text{Kcal}$

16. Price of food taken as money spent for food (see note 12) divided by Kcal value (see note 4):

Price $= \dfrac{\$1.25 \times 10^9}{1.5 \times 10^{12} \text{ Kcal}}$

$= \$.834 \times 10^{-3}/\text{Kcal of food energy}$

17. Personal communication with Steve Windham.

18. Aerial maps photographed January, 1973 (see Table 10), were planimetered for areas. Developed land consisted

of man-made lakes and reservoirs, cleared land and roads,
open space and recreation, transportation terminals,
commercial, industrial, and residential land uses.

19. Aerial maps photographed January, 1973 (see Table 10),
were planimetered for areas. Natural areas consisted of
rivers, streams, lakes, fresh and salt water marshes,
mangroves, pinelands, cypress, hardwoods, sawgrass marsh,
marl prairies, and estuarine water.

20. National average statistic of 1600 lbs/person/yr.
Total = $1600 \times 1.342 \times 10^6 = 2.15 \times 10^9$ lbs/yr
$= 1.07 \times 10^6$ tons/yr

21. Based on budget assumed to be 1% of building growth in
private sector or 1.53×10^6 ft^2/yr.

22. Value of building permits in 1972 was $\$1.3 \times 10^9$. Cost
per square foot is approximately \$8.50. Thus, the number
of square feet built is approximately 1.53×10^8 ft^2/yr.

23. Structure can be measured physically by use of material
weight or square feet of floor space. Value of building
permits from 1950-72 is approximately $\$9.25 \times 10^9$. Esti-
mate that it costs \$8.50 to build one square foot.
Therefore, total square footage is approximately

$$\frac{9.25 \times 10^9}{8.5} = 1.09 \times 10^9 \text{ ft}^2$$

If 5% per year depreciation is assumed from 1950 to 1972,
then a value of $.85 \times 10^9$ ft^2 is calculated as the stor-
age in 1972. This is a conservative number since the
estimated number of demolitions from 1960 to 1970 was

1300/yr while total construction per year was 15600
(Comprehensive Development Master Plan, 1973). This is
a rate of 8.3% per year.

24. Estimated by taking total deposits minus 10% which
represents approximate government deposits on a state-
wide basis. Therefore, business and personal deposits
= $.9 x 3,258,374,000 = $2.93 x 10^9. Assume 50% is
personal = $1.46 x 10^9.

25. In 1971 total retail sales were $2.82 x 10^9. Residents
accounted for approximately 85% of this which is $2.4
x 10^9. The value in 1972 was taken as this multiplied
by the ratio of population in those years (1.039).
Retail sales in 1972 were approximately $2.5 x 10^9.

26. Same as in note 24.

27. Based on government budget is approximately 1% of total
building permits. This is approximately 1.09 x 10^7 ft^2.

Notes to Table 7

1. From Auer (1974) the estimate of proven fossil fuel reserves in the U.S. is given as 4.5Q where Q = 1.06 x 10^{21} joules. The proportion of this available for Dade County is taken as this number times the ratio of population in Dade County to that of the U.S. This is 4.5Q x 1.35/210 = .03Q. If it is assumed that the efficiency of recovery is 40% (Ballentine), then the Kcal of fossil fuel available to Dade County is approximately:

   Fossil fuel = .4 x .03 x 1.06 x 10^{21} joules

   $$x \; \frac{2.389 \times 10^{-4} \; Kcal}{joule}$$

   Fossil fuels = 3.08 x 10^{15} Kcal

2. In 1972 total square footage was approximately 8.5 x 10^8 ft^2 (see note 23, Table 6).

3. Average effective buying income taken as average of value in 1950 and 1971 or

   $$\$(\frac{.665 + 4.8}{2}) \; x \; 10^9 = \$2.73 \; x \; 10^9$$

4. See note 13, Table 6.

5. Total structure built from 1950-72 is approximately 1261 x 10^6 ft^2 (see note 2). Average square footage built per year is then

   $$\frac{1261 \times 10^6 \; ft^2}{23 \; years} = 55 \; x \; 10^6 \; ft^2/yr$$

6. Tourist dollars in 1970 were approximately $3 x 10^9/ 1.267 x 10^6 which is $2.36 x 10^3/capita. In 1950 an approximate tourist dollar flow would be this times the

population, to give

$$\$(2.36 \times 10^3) \times (.495 \times 10^6) = \$1.17 \times 10^9$$

The average tourist dollar flow per year is then

$$\frac{\$(3+1.17) \times 10^9}{2 \text{ years}} = \$2.09 \times 10^9/\text{yr}$$

Money from other income in 1970 is $\$(5.7-3) \times 10^9 = \$2.7$ $\times 10^9$ where $\$5.7 \times 10^9$ is the total income. The approximate value in 1950 is the 1970 value multiplied by the ratio of the populations to give $\$1.4 \times 10^9$ in 1950. The average income per year from 1950 to 1970 is $\$(2.7+1.4)/2 \times 10^9 = \$2.05 \times 10^9/\text{yr}$. Total income per year is $\$(2.05+2.09)$ or approximately $\$4 \times 10^9/\text{yr}$.

7. See note 14, Table 6.

8. Based on mean building life of 20 years.

9. Money spent in running system internally is taken as total income minus money spent for goods (vehicles) and fuels. This is $4-(2.099+.592)$ billion dollars = $\$1.31 \times 10^9$. Money drain needed for goods and services is then taken as money for goods (mostly vehicles) plus the above number calculated for services. Thus, $\$(1.31+2.099) \times 10^9 = \$3.4 \times 10^9$.

10. See note 15, Table 6.

Notes to Table 8

1. See Table 7, note 1.

2. See Table 7, note 2.

3. See Tables 11 and 12.

4. See Table 4.

5. See Table 7, note 3.

6. See Table 6, note 13.

7. See Table 7, note 5.

8. See Table 9. Money for food, fuel, and goods amounts to $5.44 billion while that from manufacturing and property income amounts to $2.79 billion. The difference is $2.65 billion.

9. See Table 7, note 8.

10. See Table 9.

11. See Table 9.

12. See Table 9.

13. See Tables 11 and 12.

14. For a steady-state situation, assumed to be the same as production over a year.

15. See Table 12. Natural system energies in 1950 were 14.86×10^{12} Kcal (FFWE) while in 1972 they were 13.88×10^{12} Kcal (FFWE). To obtain the rate of destruction per year, subtract these two values and divide by 22 years to get

$$\frac{(14.86-13.88) \times 10^{12} \text{ Kcal}}{22 \text{ years}} = .05 \times 10^{12} \text{ Kcal(FFWE)/yr}$$

Notes for Table 11

1. Areas of systems obtained from Table 10 which was con-
   structed by planimetering an aerial photograph.

2. Natural ecosystems metabolic work is gross primary pro-
   duction and is estimated directly from the literature
   for most calculations.

3. The energy concentration factor is the ratio of the out-
   put energy flow for a particular energy conversion
   process to the sum of the input energies. If the output
   is expressed in fossil fuel equivalents (work equivalent
   to coal), then the energy concentration factor is the
   number of Kcal of a particular type of energy flow which
   can do the same work as one Kcal of coal. This factor
   allows conversion of natural energy flows to the same
   units as man's energy flows. See Methods and Table 1
   for references and further details. Some factors are
   uncertain and are marked with a question mark.

4. Column D is obtained by multiplying the work per unit
   area (column B) by the area of land (column A) and
   dividing by the energy concentration factor (column C).
   The result is Fossil Fuel Work Equivalents, FFWE
   (column D).

5. To gain perspective of various works done, annual energy
   contributions in column D are divided by the approximate
   ratio of work to money spent in the U.S. economy,
   25000 Kcal/dollar.

6. Fresh water marsh productivity estimated as 20 gC/m^2/day (Bayley and Odum, 1973; Young et al. 1974). Thus, productivity in $Kcal/m^2$/yr is

$$20.5 \ gC/m^2/day \times 9 \ Kcal/gC \times 365 \ days/yr$$
$$= 67.3 \times 10^3 \ Kcal/m^2/yr$$

7. Salt water marsh productivity estimated as 10.6 gC/m^2/day (Teal, 1962; Bayley and Odum, 1973). Productivity in $Kcal/m^2$/yr is

$$10.6 \ gC/m^2/day \times 9 \ Kcal/gC \times 365 \ days/yr$$
$$= 34.8 \times 10^3 \ Kcal/m^2/yr$$

8. Estimated productivity as 2.8 gO_2/m^2/day (Bayley and Odum, 1973). Productivity in $Kcal/m^2$/yr is

$$2.8 \ gO_2/m^2/day \times 4.5 \ Kcal/gO_2 \times 365 \ days/yr$$
$$= 4.6 \times 10^3 \ Kcal/m^2/yr$$

9. Pineland productivity estimated as 3.5 gC/m^2/day (Bayley and Odum, 1973, pg. 42) so that productivity in $Kcal/m^2$/day is approximately

$$3.5 \ gC/m^2/day \times 9 \ Kcal/gC \times 365 \ days/yr$$
$$= 11.5 \times 10^3 \ Kcal/m^2/yr$$

10. Cypress productivity estimated as 20000 $Kcal/m^2$/yr (Odum, E. P., 1971).

11. Bottomland hardwood gross production was estimated from values of a tropical rain forest (Odum, 1970) which was approximately 140 $Kcal/m^2$/day. For a 9-month deciduous period yearly productivity is approximately

$$140 \ Kcal/m^2/day \times 365 \ days \times .75$$
$$= 38.3 \times 10^3 \ Kcal/m^2/yr$$

12. Estuarine productivity estimated as 20000 Kcal/m^2/yr.

13. Mangrove productivity estimated as 9 gC/m^2/day (Snedaker and Lugo, 1973). Personal communication with Larry Burns (Center for Wetlands, University of Florida) which is

$$9 \text{ gC/m}^2/\text{day} \times 9 \text{ Kcal/gC} \times 365 \text{ days/yr}$$
$$= 29.5 \times 10^3 \text{ Kcal/m}^2/\text{yr}$$

14. Tides in Biscayne Bay. Mean tidal range in Biscayne Bay is approximately 2 feet (Tide Tables). Potential energy due to tides estimated from

Work = 1/2 $\rho g A h^2$

ρ = density of water = 1 gm/cm^3

g = gravitational constant = 980 cm/sec^2

A = area of water column = 1 cm^2

h = mean tidal height = 2 ft = 61 cm

Work = $\frac{1}{2}$ x 1 x 980 x (61)^2 = 182 x 10^4 ergs/cm^2 per rise or fall of tide.

Work = 182 x 10^4 ergs/cm^2 x 2 $\frac{\text{cycles}}{\text{day}}$ x $\frac{365 \text{ days}}{\text{year}}$ x $\frac{10^4 \text{ cm}^2}{\text{m}^2}$ x 2.39 x 10^{-11} Kcal/erg

Work = 318 Kcal/m^2/yr.

15. The length of eastward-facing shores including the mainland, the Miami Beach shoreline, Virginia Key, Crandon Park, Key Biscayne, and Elliott Key was measured as approximately 178 miles from aerial photographs (see note 1). Assume the wave energy is dissipated over a 20-foot-wide strip running along the coast. The area is then

$$\text{Area} = 178 \text{ miles} \times \frac{5280 \text{ ft}}{\text{mile}} \times 20 \text{ ft} \times \frac{1 \text{ km}^2}{10.76 \times 10^6 \text{ ft}^2}$$

$$\text{Area} = 1.75 \text{ km}^2$$

16. Beach wave energy was calculated by assuming 1-foot-high waves in South Dade County and 1.6-foot-high waves in North Dade County (Shore Protection Manual). The kinetic energy per cm of coastline is given by

$$\text{Kinetic energy} = \frac{1}{8} \rho g^{1.5} \times H^{2.5}$$

$$\text{K.E.} = \frac{1}{2} \times \left(\frac{1}{8} \times 1 \times 980^{1.5} \times 30.5^{2.5} + \frac{1}{8} \times 1 \times 980^{1.5} \times (1.6+30.5)^{2.5}\right)$$

$$\text{K.E.} = 4.18 \times 10^7 \text{ ergs/cm/sec}$$

If it is assumed that the wave energy is dissipated over a 20-foot = 610 cm side strip along the coast with 1-foot-high waves along half the coast and 1.6-foot-high waves along the other half, then the average kinetic energy per unit area is

$$\text{Kinetic energy/unit area/time} = \frac{4.18 \times 10^7 \text{ ergs/cm/sec}}{610 \text{ cm}}$$

$$= .685 \times 10^5 \text{ ergs/cm}^2/\text{sec}$$

$$= 1.64 \times 10^{-2} \text{ Kcal/m}^2/\text{sec}$$

$$\text{Kinetic energy/m}^2/\text{yr} = 516 \text{ Kcal/m}^2/\text{yr}$$

17. The wind energy dissipated to the ground through turbulent mixing was calculated for the urbanized part of the county and the natural part. Height of buildings was assumed to be 30 feet, whereas average height of vegetation was taken as 5 feet. Velocity at 100 feet elevation was approximated as 12 miles per hour. The air flow over Dade County was assumed to be that of turbulent flow over a rough plate with a logarithmic velocity

distribution (Schlichting, 1960). The energy dissipated
to the ground is given by

$$P = \frac{1}{2} \rho \times U^3 \times C_f$$

P = rate of energy dissipation/unit area

ρ = density of air

U = velocity high above the ground

$C_f = (1.89+1.62 \times \log(1/4xh))^{-2.5}$

L = length of rough plate of square dimension

h = average height of vegetation or buildings

For the urban region of 565 km^2 with average building
height of 30 feet

$$P = 300 \ Kcal/m^2/yr$$

For the natural area in the county with average vegeta-
tion height of 5 feet

$$P = 200 \ Kcal/m^2/yr$$

Average power density $= \dfrac{300 \times 565 + 200 \times 4917}{5482}$

Average power density $= 210 \ Kcal/m^2/yr$

18. The average height above sea level of Dade County is
approximately 10 feet (Buchanan, 1973). The potential
energy of water flowing to the sea would be approximately

$$\rho g \times \Delta h = 1 \ gm/cm^3 \times 980 \ cm/sec^2 \times 10 \ ft \times 30.48 \ cm/ft$$

$$= 298.7 \times 10^3 \ ergs/cm^3$$

$$\rho g \times \Delta h = 713.6 \times 10^{-8} \ Kcal/cm^3$$

The overland flow per year is 10 inches per year (Wang,
1974; Heaney and Huber, 1974). This figure multiplied
by the area of the county gives the total volumetric
flow which is

$$\text{Flow} = 10 \text{ in/yr} \times .0254 \text{ meters/in} \times 4983 \times 10^6 \text{ meters}^2$$

$$\text{Flow} = 1.2657 \times 10^{15} \text{ cm}^3/\text{yr}$$

Therefore, the energy flow is given by

$$\text{Energy/yr} = 713.6 \times 10^{-8} \text{ Kcal/cm}^3 \times 1.2657 \times 10^{15} \text{ cm}^3/\text{yr}$$

$$\text{Energy/yr} = .009 \times 10^{12} \text{ Kcal/yr}$$

The energy density is this divided by the land area of the county or

$$\frac{.009 \times 10^{12} \text{ Kcal/yr}}{4.983 \times 10^9 \text{ meter}^2} = .0018 \times 10^3 \text{ Kcal/m}^2/\text{yr}$$

This represents the work done by flowing water in the entire county.

19. Energy values and quality for fresh/salt water concentration gradients were obtained from Costanza (1975), who constructed maps of this energy potential for South Florida. Energy quality factors were calculated by consideration of osmotic pressure across a semi-permeable membrane resulting in a hydrostatic head.

20. Improved pasture productivity was estimated as 10.4 gC/m^2/day during the wet season (Bayley and Odum, 1973). If it is assumed that productivity is proportional to solar energy, then the average productivity over the year is

$$\frac{2}{\pi} \times 10.4 \text{ gC/m}^2/\text{day} \times 365 \text{ days} \times 9 \text{ Kcal/gC}$$

or $21.8 \times 10^3 \text{ Kcal/m}^2/\text{yr}$

21. Truck crops estimated as 35 $Kcal/m^2$/day (Odum, E. P., 1971; Odum, H. T., 1971).

22. Productivity of citrus crop taken as 4.3 $gC/m^2/day$ (Bayley and Odum, 1973, pg. 45) for an apple tree and adjusted for solar energy input. On a yearly basis this is

$$4.3 \ gC/m^2/day \ x \ 9 \ Kcal/gC \ x \ 365 \ days$$
$$= 14.1 \ x \ 10^3 \ Kcal/m^2/yr$$

23. See note 13, Table 6.

Notes to Table 13

1. Average mean daily insolation for each month in Miami
    was obtained from Bennett (1965). Average incident sun-
    light was calculated as 4500 $Kcal/m^2/day$. This is
    equivalent to

    > 4500 $Kcal/m^2/day$ x 365 days x 4.46 m^2 of collector
    > = 7.33 x 10^6 Kcal/yr of sunlight

2. For a four-person family water use is approximately 20
    gallons/person/day (Dr. Farber, Dept. of Mechanical
    Engineering, University of Florida). Total use is

    > 4 x 20 $\frac{gallons}{person-day}$ x 365 $\frac{days}{year}$ x 10 years
    > = 2.92 x 10^4 gallons/yr

3. Efficiency of Solar Thermal Process is approximately 65%
    (Aimone, 1974). Heat losses are

    > 7.33 x 10^6 Kcal/yr x .35 = 2.56 x 10^6 Kcal/yr

4. Assume 10-year life of the system (Aimone, 1965; Solar
    Water Heater Co., Miami, Fla.). Initial cost in a new
    house for an 80-gallon tank and 48 ft^2 Collector is
    $650. Cost of an immersion heater back-up system is $7.
    In Kcal this was

    > $657 x $\frac{25000 \text{ Kcal}}{\text{dollar}}$ = 16.4 x 10^6 Kcal

    Initial plus installation costs in an old house were
    $657 + $144 = $801 which is

    > $801 x $\frac{25000 \text{ Kcal}}{\text{dollar}}$ = 20 x 10^6 Kcal

    Depreciation was

    > New house: .1 x 16.4 x 10^6 = 1.64 x 10^6 Kcal/yr
    > Old house: .1 x 20 x 10^6 = 2 x 10^6 Kcal/yr

5. See note 2. Assume 10% heat loss from water tank and water heated by 39.°C temperature increase

$$29.2 \times 10^3 \frac{gal}{year} \times \frac{3.785 \ Kg}{gal} \times \frac{1 \ Kcal}{Kg\text{-}°C} \times 39°C$$
$$= 4.3 \times 10^6 \ Kcal/yr$$

6. Additional electrical energy is needed during the months of January, February, October, November, and December. Using the data from Bennett (1965), this amounts to 476.3 Kwh/yr. In FFWE this is

$$476.3 \ Kwh/yr \times \frac{860 \ Kcal}{Kwh} \times 4 = 1.64 \times 10^6 \ Kcal/yr$$

7. Amount of electrical energy can be obtained from note 6 and is

$$476.3 \ Kwh/yr \times 860 \ Kcal/Kwh = .41 \times 10^6 \ Kcal/yr$$

8. For interest rate of 10%/yr and lifetime of 10 years the amortization factor was .163. The costs per year were

New house: $657 x .163 = $107/yr

Old house: $801 x .163 = $130/yr

9. Assume 10% loss of heat from hot water tank. Multiply value in note 5 by .1 to get .43 x 10^6 Kcal/yr.

10. See note 8.

New house: $107/yr x 25000 Kcal/dollar
$$= 2.7 \times 10^6 \ Kcal/yr$$

Old house: $130/yr x 25000 Kcal/dollar
$$= 3.3 \times 10^6 \ Kcal/yr$$

11. See note 5. Assume 10% loss so that total heat required is

$$(4.3+.43) \times 10^6 \ Kcal/yr = 4.73 \times 10^6 \ Kcal/yr$$

12. See note 6. Additional energy is 476 Kwh/yr. Average cost per Kwh was approximately $.023/Kwh for an average monthly consumption of 1000 Kwh (Fla. Power and Light Corp.). The fuel adjustment was

476 Kwh/yr x $.009/Kwh = $4.29

Total price

$10.95 + $4.29 = $15.24/yr

13. Costs quoted by the Solar Water Heater Co., Miami, Fla., Mr. Morrow, President. See note 4 for detailed costs.

Notes to Table 14

1. See Table 13, note 2.

2. 5% of 4.73×10^6 Kcal/yr = $.24 \times 10^6$ Kcal/yr.

3. Assume 10%/yr depreciation:

   $$.1 \times 3.3 \times 10^6 \text{ Kcal} = .33 \times 10^6 \text{ Kcal/yr}$$

4. See Table 13, note 9.

5. See Table 13, note 5.

6. Amount of heat required for hot water is 4.73×10^6 Kcal/yr. If the electrical system is 95% efficient, 4.98×10^6 Kcal/yr is required or 5.79×10^3 Kwh/yr.

7. Average cost of electricity is \$.023/Kwh (see Table 13, note 12) with a fuel adjustment of \$.009/Kwh.

   $$\text{Cost} = 5.79 \times 10^3 \text{ Kwh/yr} \times (\$.023/\text{Kwh} + \$.009/\text{Kwh})$$
   $$\text{Cost} = \$185/\text{yr}$$

8. From note 6 annual consumption of electricity is 4.98×10^6 Kcal/yr. This is equal to

   $$4 \times 4.98 \times 10^6 \text{ FFWE/yr} = 19.9 \times 10^6 \text{ FFWE/yr}$$

9. See note 12 for cost of equipment. Assuming an equipment lifetime of 10 years and an interest rate of 10%/yr, the amortization factor is .163. The annual cost is then $.163 \times \$132 = \$21.5/\text{yr}$.

10. See note 9. The energy cost for the equipment would be

    $$\$21.5/\text{yr} \times 25000 \text{ Kcal/dollar} = .54 \times 10^6 \text{ Kcal/yr}$$

11. See Table 13, note 11.

12. Sears Roebuck costs listed as

Cost of heater =	\$75.00
Cost of installation =	57.00
	\$132.00

$132 x 25000 Kcal/dollar = 3.3 x 10^6 Kcal

13. The total natural gas needed to provide hot water is 5.91 x 10^6 Kcal/yr (see note 14). Gas burns 80% efficiently so that .2 x 5.91 x 10^6 Kcal/yr = 1.18 x 10^6 Kcal/yr is lost.

14. The amount of heat energy required to heat the water is 4.3 x 10^6 Kcal/yr (see note 5). If 10% loss from tank is assumed, then 4.3/.9 x 10^6 Kcal/yr = 4.73 x 10^6 Kcal/yr is needed to heat water entering tank. Natural gas burns 80% efficiently so that 4.73/.8 x 10^6 Kcal/yr = 5.9 x 10^6 Kcal/yr of natural gas is needed.

15. Cost of natural gas is natural gas use times price or
5.91 x 10^6 Kcal/yr x ($1x$10^{-5}$/Kcal) = $59.1/yr

16. Sears Roebuck gives costs of a natural gas water heater as follows:

Initial cost = $115
Installation = <u> 57</u>
$172

Amortize cost over ten years for interest rate of 10% gives a total cost of 172 x (.163) = $280 or $28/yr which is
$28/yr x 25000 Kcal/dollar = .7 x 10^6 Kcal/yr

17. Initial cost of equipment is $172 or
$172 x 25000 Kcal/dollar = 4.3 x 10^6 Kcal

Notes to Table 18

Figures are approximately 1965-66 values.

Assume that the natural energies balance the losses to maintain a steady-state in the natural system. Thus, $S = K_1 Q_1$ where it is assumed that $K_1 Q_1 = 0.02\ Q_1 = 2\%$ of Q_1/yr.

1. Ecosystem lands - Upland forests $\simeq 18.5 \times 10^6$ acres

   Mangrove $\simeq$ $\underline{0.691 \times 10^6\ acres}$

   19.19×10^6 acres

2. Disordered parts - Bombed

Agriculture:	31000 acres
Forest:	9030 acres in craters
City:	$\underline{890\ acres}$
	4.092×10^4 acres

   Herbicided

Forest:	150000 acres
Agriculture:	$\underline{5.94 \times 10^4\ acres}$
	21×10^4 acres

   TOTAL: $Q_2 \simeq 25 \times 10^4$ acres

3. Agricultural land $\simeq 7.31 \times 10^6$ acres.

4. Urban land $\simeq 2.47 \times 10^4$ acres.

5. Capital in city $\simeq$ \$281 million

6. Herbicide use -
Agricultural land:	198×10^3 gallons
Upland forest:	455×10^3 gallons
Mangroves:	$\underline{11 \times 10^3\ gallons}$
	644×10^3 gallons

7. Communist energies - 140000 men or \$555 million.

8. Rate of growth of urban land: $K_{11}Q_1Q_2M \simeq 1235$ acres/yr

9. Bare forest land returning to agriculture:

$K_7Q_1Q_2M \simeq 5600$ acres/yr

10. Assume 50% of agricultural land replanted. Thus,

$K_8Q_3CW = 0.5[3.1 \times 10^4 + 5.94 \times 10^4] \simeq 4.5 \times 10^4$ acres/yr

11. Ecosystem lands destroyed:

$K_3Q_1CW = 0.05[(9.03 + 150) \times 10^3] = 7.95 \times 10^3$ acres/yr

12. War appropriations from U.S.:

$W \simeq \$200$ million

13. U.S. aid:

$A \simeq \$250$ million

14. Purchased input amounts to

$K_4M \simeq \$50.3$ million

15. Amount of structure destroyed:

$K_5CW[Q_1 + Q_3 + Q_4] \simeq 40 \times 10^3$ acres/yr

16. Amount of money flowing in due to sales:

$K_{14}Q_3 \simeq \$40.5$ million

17. The amount of money flowing out to purchase goods and fuel:

Goods $= (K_{15} + K_{16})M \simeq \$130.5$ million

Fuel $= K_{16}M \simeq \$80.5$ million

18. Bare land returning to agriculture:

$K_6Q_1Q_2M \simeq 14000$ acres/yr

19. Amount of natural land changing into urban land:

$K_{11}Q_1Q_2M \simeq 1235$ acres/yr

20. Amount of natural land converted into agricultural land:

$K_7Q_1Q_2M \simeq 5600$ acres/yr

21. Rural destruction:

$$K_8 Q_3 CW \simeq 4.5 \times 10^4 \text{ acres/yr}$$

22. Rate of return of disordered land to natural land:

$$K_0 Q_2 \simeq 1.25 \times 10^4 \text{ acres/yr}$$

23. Ecosystem destruction due to herbicide:

$$K_{31} Q_1 H \simeq 1.5 \times 10^5 \text{ acres/yr}$$

24. Agricultural land destroyed by herbicide:

$$K_{30} Q_3 H \simeq 5.94 \times 10^4 \text{ acres/yr}$$

25. Total herbicide destruction:

$$K_{21} H(Q_1 + Q_2 + Q_4) \simeq 21 \times 10^4 \text{ acres/yr}$$

26. Urban bomb destruction:

$$K_{13} Q_4 CW \simeq 890 \text{ acres/yr}$$

27. Total ecosystem transformation into rural and urban:

$$K_2 Q_1 Q_2 M \simeq 1235 + 5600 = 6835 \text{ acres/yr}$$

28. Assume approximately 2% recycle into Q_2 from Q_1, Q_3, and Q_4; $K_1 \simeq K_9 \simeq K_{12} \simeq 0.02$.

Notes to Tables 19-22

1. Numbers compiled in Table 19 were obtained from Minerals
   Yearbook (1950-1970) and from several Mineral Industry
   Surveys. Fuels used by the Electric Utilities Industry
   have not been included since kilowatt-hour data have been
   compiled for Dade County. The Minerals Yearbook did not
   include figures for distillate, residual, kerosene and
   liquid petroleum fuels in 1967 and 1968. It also did not
   list electric utility consumption of distillate, residual
   and kerosene fuels from 1950-53 and from 1961-68. Per-
   centage used by electric utilities for the years 1954-56
   was approximately 44% so it was assumed this was true for
   1950-53. For 1961 this percentage was 39%, whereas for
   1969 it was 57%. It was assumed that this percentage
   increased linearly from 1961-69 in order to obtain the
   figures in Table 1.

2. Most data in Table 20 were obtained from various county
   and state publications listed in the references.

3. Square footage was approximated by dividing value of
   building permits by average building cost of $850/ft^2.

4. Consumption of distillate, residual, kerosene and liquid
   petroleum fuels was obtained by multiplying the Florida
   consumption by the population ratio to arrive at the Dade
   County estimate. It was felt that this was a good esti-
   mate since, aside from the electric utilities, most of
   this fuel is residentially and commercially consumed.

5. Total gasoline sales were obtained from the Dade County Department of Transportation.

6. If the total consumption of natural gas in Florida for 1971 is multiplied by the ratio of the populations of Dade County to the population of Florida for 1971 (1.3154/7.041 = .1868), a total consumption of 25500 x 10^6 ft^3 is obtained for the county. This would be a good approximation if the mix of commercial, residential and industrial sectors was homogeneous throughout the state. A correction for this ratio was calculated by finding out the actual natural gas sales for Miami from the Annual Report of Florida Gas Co., 1971, calculating a per capita consumption for Miami, and then multiplying this by the total population of Dade County to obtain a more accurate consumption figure for the county. This turned out to be 11337.5 x 10^6 ft^3. The ratio of this figure to that calculated from Florida data is .444 (11357.5/25500). With the aid of this correction the consumption in Dade County was calculated for each year by multiplying the Florida consumption by the population ratio times .444.

7. Kilocalorie energy values of the various fuels were obtained by using the following conversion factors (Federal Power Commission, 1970):

Natural gas: 1075 BTU/ft^3 x .253 Kcal/BTU
= 271.975 Kcal/ft^3

Residual, distillate and kerosene fuel:
6.4 x 10^6 BTU/barrel x .253 Kcal/BTU
= 1.6192 x 10^6 Kcal/barrel

Liquid petroleum: 4.011 x 10^6 BTU/barrel

x .253 Kcal/BTU = 1.014783 x 10^6 Kcal/barrel

Gasoline: 3.6 x 10^4 Kcal/gal

Electricity: 1 kilowatt-hour = 859.85 Kcal

Electrical energy is considered to be a high quality energy which is easy and clean to distribute. In order to achieve this high quality approximately 4 units of lower quality coal or oil must be consumed (this ratio includes maintenance costs; see Table 1). In order to put the kilowatt-hour consumption on the same energy reference level as natural gas and liquid fuels, the electrical energy use should be multiplied by four. The total energy was calculated by the following formula:

Total energy = natural gas + (distillate, residual and kerosene fuel) + liquid petroleum fuel + gasoline + 4 x (electrical energy)

8. Per capita data were obtained by dividing total figures for county by total population.

9. First differences give an indication of the rates of change from year to year.

APPENDIX III

SCALED EQUATIONS FOR MODELS SIMULATED

Model in Fig. 20

$$\frac{\dot{Q}_1}{2 \times 10^9} = .3 \times \frac{F}{7.7 \times 10^{15}} \times \frac{Q_1}{2 \times 10^9} \times \frac{M}{10^{10}} - .05 \times \frac{Q_1}{2 \times 10^9}$$

$$\frac{\dot{F}}{7.7 \times 10^{15}} = -.11 \times \frac{F}{7.7 \times 10^{15}} \times \frac{Q_1}{2 \times 10^9} \times \frac{M}{10^{10}}$$

$$\frac{\dot{M}}{10^{10}} = .468 \times \frac{I_2}{10^{10}} - .681 \times (10) \times \frac{F}{7.7 \times 10^{15}} \times \frac{Q_1}{2 \times 10^9}$$

$$\times \frac{M}{10^{10}} \times \frac{P_1}{.804 \times 10^{-4}} - .15 \times (100) \times \frac{M}{10^{10}} \times \frac{P_1}{.804 \times 10^{-4}}$$

$$\frac{\dot{P}}{.804 \times 10^{-4}} = 0 \text{ before 1973}$$

$$\frac{\dot{P}}{.804 \times 10^{-4}} = \text{constant after 1973 depending on inflation rate}$$

Model in Fig. 24

$$\frac{\dot{Q}_1}{2 \times 10^9} = .129 \times (10) \times \frac{E}{300 \times 10^{12}} \times \frac{Q_1}{2 \times 10^9} \times \frac{M}{10^{10}}$$

$$- .48 \frac{Q_1}{2 \times 10^9} \times \frac{Q_1}{2 \times 10^9}$$

$$\frac{\dot{M}}{10^{10}} = .015 \frac{I_2}{10^{10}} - .855 \times (10) \times \frac{E}{100 \times 10^{12}} \times \frac{Q_1}{2 \times 10^9} \times \frac{M}{10^{10}}$$

$$\times \frac{P_1}{.804 \times 10^{-4}} - .15 \times (100) \times \frac{M}{10^{10}} \times \frac{P_1}{.804 \times 10^{-4}}$$

Model in Fig. 27

$$\frac{\dot{P}}{.804 \times 10^{-4}} = 0 \text{ before 1973}$$

$$\frac{\dot{P}}{.804 \times 10^{-4}} = \text{constant after 1973 depending on inflation rate}$$

$$\frac{\dot{Q}_1}{2 \times 10^9} = .31 \times \frac{F}{7.7 \times 10^{15}} \times \frac{M}{10^{10}} \times \frac{Q_1}{2 \times 10^9} - .05 \times \frac{Q_1}{2 \times 10^9}$$

$$\frac{\dot{Q}_2}{20 \times 10^{12}} = .144 \times (10) \times \frac{Q_2}{20 \times 10^{12}} \times \frac{J_R}{2 \times 10^{15}}$$

$$- .008 \times \frac{Q_1}{2 \times 10^9} - \frac{Q_2}{20 \times 10^{12}}$$

$$\frac{\dot{Q}_3}{10^7} = .159 \times \frac{F}{7.7 \times 10^{15}} \times \frac{M}{10^{10}} \times \frac{Q_1}{2 \times 10^9} - .014 \times \frac{Q_3}{10^7}$$

$$\frac{\dot{M}}{10^{10}} = .145 \times \frac{\frac{F}{7.7 \times 10^{15}} \times \frac{Q_1}{2 \times 10^9} \times \frac{Q_2}{20 \times 10^{12}}}{\frac{P_2}{.804 \times 10^{-4}}} + .535 \frac{Q_3}{10^7}$$

$$- .18 \times (10) \times \frac{Q_3}{10^7} \times \frac{M}{10^{10}} - .3 \times (100) \times \frac{M}{10^{10}}$$

$$\times \frac{Q_1}{2 \times 10^9} \times \frac{F}{7.7 \times 10^{15}} \times \frac{P_1}{.804 \times 10^{-4}}$$

$$\frac{\dot{F}}{7.7 \times 10^{15}} = -.102 \times (10) \times \frac{F}{7.7 \times 10^{15}} \times \frac{M}{10^{10}} \times \frac{Q_1}{2 \times 10^9}$$

$$\frac{\dot{J}_R}{2 \times 10^{15}} = .7 - .144 \times (10) \times \frac{J_R}{2 \times 10^{15}} \times \frac{Q_2}{20 \times 10^{12}}$$

$$\frac{\dot{P}_1}{.804 \times 10^{-4}} = 0 \text{ before 1973} \qquad \frac{\dot{P}_1}{.804 \times 10^{-4}} = .02 \text{ after 1973}$$

$$\frac{P_2}{.804 \times 10^{-4}} = .007 \text{ before 1973} \qquad \frac{P_2}{.804 \times 10^{-4}} = .011 \text{ after 1973}$$

Model in Fig. 38

$$\frac{\dot{Q}_1}{10^6} = .384[S] + .5[Q_2] - .134(10)[Q_1][C][W] - .6[Q_1]$$

$$- .234[Q_1][H] - .15(100)[Q_1][Q_2][M]$$

$$\frac{\dot{Q}_2}{.33 \times 10^6} = .14[M] + .5[C][W](.3[Q_1]+.0098[Q_3]+.0098[Q_4])$$

$$+ .5(.142(100)[Q_1]+.475[Q_3])[H]$$

$$- .938(100)[M][Q_2][Q_1] + .18(10)[Q_1]$$

$$+ .06(10)[Q_3] + .06[Q_4]$$

$$\frac{\dot{Q}_3}{.33 \times 10^6} = .365(100)[M][Q_1][Q_2] - .2(100)[Q_3][C][W]$$

$$- .6[Q_3] - .244[Q_3][H]$$

$$\frac{\dot{Q}_4}{.33 \times 10^5} = .11(1000)[Q_1][Q_2][M] - .6[Q_4] - .117(1000)$$

$$\cdot [Q_4][C][W]$$

$$\frac{\dot{M}}{.33 \times 10^3} = .166[Q_3] + .15(10)[A] - .86(10)[M]$$

$$- .86(10)[M] + .18(100)[W]$$

Maximum Values:

$Q_{1m} = 30 \times 10^6$ $\qquad Q_{3m} = 10^7$ $\qquad C_m = 2 \times 10^3$ $\qquad A_m = 500$

$Q_{2m} = 10^7$ $\qquad M_m = 10^4$ $\qquad W_m = 6 \times 10^3$ $\qquad H_m = 1$

Brackets represent scaled variables. For example, $[Q]$ = Q/Q_{max}. See Methods section.

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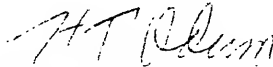
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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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